STUDENT MANUAL
Astronomy 104 Laboratories
Fall 2022
University of Mississippi

(Astronomy 103 classes have a different laboratory manual.)

Please take this manual with you for every laboratory session.
You’ll need its tear-out pages for turning in your lab report!
Lab #1: Introduction and syllabus

WELCOME TO ASTRONOMY!

In the beginning of the first laboratory your instructor will distribute the syllabus and explain what you need to do during laboratory sessions, what you have to have each time with you, how to prepare for each lab, and how your grade will be calculated. After that you proceed to one of the laboratory exercises in this manual.
Lab #2: Visit Kennon Observatory

Astronomical telescopes come in two types, according to what their main optical element is: (i) refractors, which use a lens to collect light and form an image of the observed object, and (ii) reflectors, which use a concave mirror for that purpose. They serve the two main purposes of astronomical instruments: (1) collecting as much light as possible, and (2) seeing as small details as possible. The most important factor for both of these purposes is the diameter of the lens or mirror. Modern 21\textsuperscript{st} century telescopes are all reflectors, because it is just too hard to make a lens (which has to be supported at the edges and sags) larger than a yard in diameter. You can immediately tell whether a reasonably large telescope is a reflector or a refractor by the way it looks (see the pictures): refractors normally come in very long tubes because their lenses have long focal lengths. It would be very hard to make a good large lens with a short focal length since it would bulge out in the middle and be extremely heavy.

The main telescope in the large dome of Kennon Observatory is a 15-inch refractor. At the time when it was built (1892) it counted as a research-grade telescope. Of course, it has historical value only in the 21\textsuperscript{st} century, but it is still used for educational purposes. As a classical refractor, it has a very long focal length ($f = 180$ inches). Through such a long tube you can see only a very small part of the sky at a time, so this telescope is not very convenient for viewing extended object such as galaxies or nebulae, but it is ideal for observing binary stars, the planets and the Moon – everything where good resolution matters. In really calm weather when the blur due to the atmosphere (called “seeing”) is little, this lens can resolve details as small as $1/3$ arc second; it allows a detail-rich image even at as high magnification as $400 - 500 \times$. On most nights, however, the motion of the air limits the resolution and only lower magnification can be used.

Astronomical telescopes must be supported by very firm mounts. Any little shaking renders even a good quality lens completely useless, because the shaking is magnified by the telescopes.
as much as the observed object is. The mount should allow the telescope to turn around an axis that is parallel to the axis of Earth (the right ascension axis) at a steady rate of one turn a day to track the stars automatically as they move in the sky. A clock drive is built into the mount to do this. In order to point at a star of the observer’s choice, the telescope can be turned around another axis (the declination axis) as well. This arrangement of a mount is called an equatorial mount. There are two types of mounts normally used for all but the very biggest telescopes: (i) the fork mount, and (ii) the German mount (see the picture). German equatorials are usually more expensive to make, but they are also more precise and more robust – the 15-in refractor is on a German equatorial mount.

In the late 1850s the University of Mississippi, under the leadership of Chancellor Barnard, decided to build the world’s largest telescope. The design of the building to house the telescope followed that of the famous Pulkovo Observatory built in 1839 outside St. Petersburg, Russia. In January 1863, Alvan Clark, of Massachusetts, who later made the largest lens in the world (the 40-inch refractor in Yerkes Observatory in Wisconsin), finished grinding and polishing Barnard’s 19-inch lens and tested it on Sirius, the brightest star in the sky. During this testing he made one of the most important discoveries in 19th century astronomy: he discovered the white-dwarf companion star of Sirius, now called Sirius B. This star is as heavy as the Sun but only as large as Earth! Unfortunately, the Civil War broke out, and Mississippi could not muster the payment due on the lens that would have made Ole Miss the leading astronomical institution in the country. It ended up at Northwestern University in Illinois.

By the time Barnard Observatory received its telescope in 1893, the 15-inch refractor, built by Sir Howard Grubb of Dublin, Ireland, did not make it among the largest telescopes of the world. Observatories also started to be built in locations with much better seeing, less moisture and fewer clouds on mountaintops. No more cutting-edge observational research was possible in locations like Oxford.

The 15-inch telescope was relocated to the Kennon Observatory in 1939. Its outdated mechanical clock drive was replaced by an electrical drive in 1953, and modernized again in 2010. As the telescope was designed for research work to observe the same object for days at a time, setting it up and aiming it at a new object is a slow process. For this reason it can be used in astronomical teaching laboratories only a few times a year.
PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: __________ Partner’s name: __________ Section: __

1. Read the review, and listen to your instructor’s introduction.

2. Answer the following questions about telescopes:
   -- What are the two main purposes of a telescope in astronomy?
     1 _____________________, 2 ______________________________
   -- If a telescope has a very long and narrow tube, its main optics must be a ____________.
   -- The telescope in the large dome is a ref__ctor, its main optics is a ________, and
     in very good weather it can use a magnification as large as ______.
   -- The telescope should be turned by the clock drive one turn per _____ hours to track
     the stars around the ______________ axis which points at the ______________.
     The other axis is called the __________ axis, and a mount whose axes are arranged
     this way is called an ________ mount.

3. Answer the following questions about our telescopes:
   -- What famous discovery was made with the telescope that had been made on the order
     of Ole Miss Chancellor Barnard? _____________________________
   -- Why has this telescope never arrived at Ole Miss? _________________
   -- How old is the telescope in the large dome? ______years. How large is it? ___________
   -- Is the telescope in the large dome good for research?
     Give a reason: _______________________________

4. Now follow your TA to the large dome for a visit.

5. Answer the following questions about your visit:
   -- The large telescope in the large dome is a ref__ctor, which means that its main optical
     element is a _______.
   -- The way we refer to the telescope is “the ___-inch telescope”, and the number
     refers to the __________ of its main optical element.
   -- The mount of this telescope is a(n) ______________________.
   -- The slit on the dome is closed when it is raining. How do you think observations are done
     at those times? _______________________________


Lab #4a: Spherical Astronomy

The way stars move in the sky is actually quite easy to understand. All they do is they make one circle in \(23^\text{h}56^\text{m}\), around the North (and South) poles. This is called sidereal motion - one circle (360°) every 24\(^h\), which simplifies to 15° per hour: the sidereal rate. Of course, this is a reflection of the rotation of Earth. When we look towards the South, the stars slowly “drift” from left to right; that is, they rise in the East and cross the meridian high up in the South (this is called culmination, or transit from the eastern sky to the western sky). When you look towards the North, you see the stars slowly go in circles around the North Pole, coming up on the eastern side, culminating, and going down on the western side.

You’ll use the concepts of Zenith straight above you, Nadir directly under you, and the horizon – that is where stars rise or set.

PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: ______________ Partner’s name: ______________ Section: __

Questions 1 through 8 need no advance knowledge in astronomy. Use common sense to figure out the answers to these. You may ask your instructor for advice on how good your reasoning is, but you will have to do the actual thinking.

Picture 1 shows the sky from the perspective of an observer in Mississippi’s 34° latitude. The cardinal directions (E, S,W, N) are on the horizon; these are the directions we use in everyday life.

1. Identify the following in Picture 1. Use the requested letters or colored pencils to draw: Horizon (green), Meridian (red), North Pole (NP), Zenith (Z), Nadir (N), Equator (blue).

2. Take the star that rises exactly in the East. Indicate its position with a blue star shape ★ when it is rising, green ★ high up before transit, red ★ when culminating, yellow ★ after transit, and orange ★ when setting. When can you see this star in the northern sky? ______________ How many hours will this star take from rising to transiting? ______________ Is this star under, on, or over the equator? ______________
3. Use Picture 2 to draw. Take the star that culminates at zenith, draw its path across the sky in black with an arrow showing the direction of its motion, and repeat Exercise #2 (drawing the colored stars). Based on the length of its path over and under the horizon, will this star be up longer or down longer every day?

4. Still in Picture 1, indicate the path of Polaris across the sky with a red line, and mark it with a red P.

5. In Picture 2, indicate the way the Sun moves in the sky during one day (i) in the summer (red), and
(ii) in the winter (blue).

6. Read off from your drawing where the sun rises/sets: in the summer: ____/____; and in the winter: ____/____.

7. Picture 3 indicates the way the sky moves from two locations. Where on Earth are they? Write your answers under the pictures.

8. Why can the planets never be in the northern sky? ________________________________
9. In Picture 4, you see a person standing on Earth. Indicate in each of three cases what time it is and whether the Moon is rising, setting, culminating, or not up at all.

![Picture 4](image)

The angular distance of a star over the equator is called its declination, as Picture 5 indicates.

10. **Declination.** Based on this picture, what is the declination of Polaris? _________ What is the declination of a star that is located on the equator? _______________ And a hard question: the most spectacular globular cluster in the sky is ω Centauri. It barely comes up for a few minutes and goes down immediately. What is its declination? _______________
Lab #4b: Find Objects with SkyGazer

In this exercise we use SkyGazer planetarium software to look up objects in the sky. This is how you do actual observation in astronomy: find out where your object is in the sky, how it looks and when is it visible. Only then can you go to a telescope and successfully find the object in the sky.

**PROCEDURE AND LAB REPORT**

Date:__/__/20__. Your name: __________ Partner’s name: __________ Section: __

1. **Start up SkyGazer** (quit it first if it is running!) by double clicking on the setup file *FindObjects.vgr*, located in the *AstroLabs/AstroDocuments* folder. On the time panel click *Now*, then drag the hand of the clock to 10 pm.

2. First, find the star µ Cephei, a carbon star famous for its very deep red color. It is, obviously, in the constellation Cepheus. So, switch on constellations [constellations] and constellation boundaries [constellation boundaries], and use Center→Constellations→Cepheus→Center. You’ll see the constellation and look up µ Cep within its boundaries. (If the field is too cluttered, you may have to zoom in a bit, then drag the sky with the mouse.) When you have found it, click and center, then zoom in. You will notice that it moves (this is the usual sidereal motion.) To follow its motion, click [Lock]. Now read off its data:

   Name: µ Cep   Brightness: ______ What object: Star   Spectrum: _____ Color: ______.
   Distance: ______ Transit time: ______ Sets: ______ Rises: ______.

When is µ Cep visible? Zoom back out to 120° view, unlock, grab the clock and move it along the night, and see when µ Cep is highest up. Astronomical objects are not easily observable when they are not higher up than 30°. So you would look for µ Cep in the sky at ______.

3. Next, find the Orion Nebula in the winter, or the Ring Nebula in the summer. Because they are on the list of the ~100 brightest deep sky objects (the Messier Catalogue) under the names M 42 and M 57 respectively, you can shortcut the procedure by using the menu Center→Messier Object→M 42/57→Center. Now, the same way as with µ Cep, determine when you would observe your nebula:

   Name: The Nebula (M__)   Brightness: ___ What object: ________________________
   Distance: _____ Transit time: ___ Sets: _____ Rises: ______. Observe at: ______.

   (For the object type, chose one of the six standard types of deep sky objects: open cluster, globular cluster, diffuse nebula, planetary nebula, galaxy, or supernova remnant.)
4. Next, try the find the other nebula in Exercise 2. You may get a message that the object is below the horizon; in that case, do not use the Star Atlas mode! Rather, drag the clock and see if the object is up at all tonight. In any case, fill out the rest of the data, and answer “unobservable” to the last question.

Name: The Nebula (M )  Brightness: ___  What object: ________________________.


5. Next, someone reported that he or she observed a supernova in a galaxy and gave the coordinates RA=9h55m08.9, DEC=69°38′54″ (2000.0). Find this supernova’s location in the sky. You can set the precession epoch under Chart→Set Precession→(Year). Switch to __________-view, then see that the data bar __________ indicates the coordinates of the center of the field. (The box switches the data bar on/off.) Switch on ______ the coordinate grid. To have sufficient precision, you’ll have to zoom __________ in as you drag the sky with the mouse to the correct place in the sky. Find the data of the host galaxy, and draw the location of the supernova in the galaxy. (Have North up; use a 20′×~15′ view to match the scale with the size of the box below. Indicate the galaxy, its name, a few stars, and put a cross with SN for the location of the supernova. Your star chart can now be used at the telescope.)

Name: _________  Brightness: ___  What object: _________  In what constellation: ________,

6. Up to this point, in each exercise you had the steps given to you in full detail. Now, use your own skills and repeat the procedure for a collection of objects. On the way, you’ll practice recognizing the six types of deep sky objects, and you’ll get used to some of the constellations. Depending how much time you have, your instructor may ask you to do more or less of this list.

The full list: M 1, M 13, M 20, M 27, M 31, M 45, M 51; ε Aurigae, β Cygni, and the star at RA=14^h29^m42.2^s, DEC=−62°40′38″ (2000.0).

Use the following slots to fill in the data:

Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.
Name: _______ Brightness: ___ What object: _______ In what constellation: _______,
Distance: ____ Transit time: ____ Sets: ____ Rises: _______. Observe at: _______.

Lab #5b: Orientation with SkyGazer (Oct to Mar)

Computer software can be great help in finding objects, stars, constellations, and even planets in the sky. It is called “planetarium software” because it presents on the screen something remotely resembling the artificial sky of a planetarium. You can simulate the sky at any time, from any location on Earth, and switch interesting and uninteresting objects on and off at will. In this laboratory you’ll get familiar with the menus and options in one of these programs (called SkyGazer), and, on the way, you will learn about the names, the brightnesses and colors of stars, in addition to finding constellations and planets.

This piece of software comes with the textbook (if you bought it new), and you may install it on your computer without a fee. Your instructor may arrange to lend you an installation CD if you request it.

The computers in the lab are all Macintosh, and those of you only familiar with Windows machines should be prepared for minor differences. The first point of difference you will see is that the SkyGazer application does not quit if you close its window. If you find your computer in that state, double-clicking of your setting file will still start up the program the same way as it would in Windows.

In case the lecture has not yet covered the concepts of magnitudes, right ascension and declination, equator and ecliptic, ask your lab instructor to give an introduction.

PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: __________ Partner’s name: __________ Section: __

1. **Start up SkyGazer** (quit it first if it is running!) by double clicking on the setup file Orientation.vgr, located in the AstroLabs/AstroDocuments folder.

2. On the time panel click *Now*. Then drag the hand of the clock to 10 pm. Many stars show up, colored, and it is very hard to make sense of them now.

3. Use the sliding tabs in the bottom and on the right to turn towards North and experiment with looking high up or lower down. Stop in direction of North. Use the pop-up compass if you need to. Straight North, not very high over the horizon, you’ll find the North Star (Polaris). Click on it. The data panel pops up. Find out the North Star’s data: it is in the constellation of __________, and it is a ___ magnitude star, ____ light years away from us. Center it by clicking *Center*. Compare it to a few other stars: is it the brightest star in the sky? ___.

4. On the display panel, switch on the constellations (click on ). The contours of some constellations pop up. Find the familiar shapes of the Big Dipper and the Little Dipper. In which one of these is Polaris? ________________
5. **Switch on** the constellation figures (click on ![constellation figures](image)). You’ll see that the Dippers are actually bears, and Draco (which is a kite rather than a dragon) is between them.

Now turn South again. Drag the hand on the clock until the bright constellation of Orion is not far from South. (This will happen at different hours in the night depending on the season.)

Find, Canis Maior, and Taurus. Find the names of the two brightest stars in Orion, and also the brightest star in the sky, located in Canis Maior, and read off their data:

- α Orionis is named __________, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____;

- β Orionis is named __________, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____;

- α Canis Maioris is named ______, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____;

the brightest of these is _________ with ___ magnitudes; its magnitude is the ____est number.

6. **Look straight up** into Zenith, and find the Twins, the star Capella, and the Seven Sisters.

Find these stars and read off their data:

- α Geminorum is named __________, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____;

- β Geminorum is named __________, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____;

- α Aurigae is named ______________, ____ light years away, ___ magnitudes;
  
  spectral type ____, color ____.

Now switch on the constellation boundaries ![constellation boundaries](image).

The Seven Sisters, officially named the Pleiades, are within the constellation of __________.

7. **Now switch off** the constellation figures, and switch on the Milky Way (click on ![milky way](image)). Follow it from horizon to horizon, and write down which constellations it crosses in the sky (list only the ones that are visible at 9 pm tonight). Notice that the names of small constellations show up only if you zoom in (use ![zoom](image) to zoom):

____________________________
__________________________________________________________________________.
8. **Now look at Polaris** again, set the time skip to 1 min, and start the clock. You will see that the sky revolves around Polaris as time passes. What is special about the daily motion of Polaris? ____________________________________________.

9. **Look South**, set the clock to 9 pm tonight, and zoom to a 120° view. Turn on the ecliptic and the equator by clicking on . The ecliptic (the path the ____ travels once a ____ ) is the _____ line, the equator is the ____ line. (Fill in the colors.) Find all the planets that are up. They are all located close to the ____________. Give the name of each, then their magnitude in parentheses together with words “bright” or “faint” like Sun (-26.3mg, very bright):

   _____________________________________________

10. **Set the clock to now.** Give the name of two conspicuous constellations that are high up in the South now: _______________ and _______________.

11. **Find a planet that is not up now:** ________. Click View→Center Planet→(Your planet); do not use the Sky Atlas mode. on the planet, then drag the clock and watch at what time it rises. To observe a planet conveniently it needs to be at least 25° over the horizon (i.e. its altitude on the data panel must be at least 25°). You find that your planet is observable only after from ____ to ___. (Give the hours; use common sense in judging when the planet is actually observable!) Drag the clock further to find out when your planet is best observable; that is, when it is highest over the horizon. This occurs at _____ o’clock, and at that time your planet is in the _______ (fill in the cardinal direction). Today, your planet is as bright as ____ magnitudes, which means, in words, ______________. It is located in the constellation of ___________. Is it close to the ecliptic? ____________.

12. **Find the Moon.** The Moon is _____ days old today, it is in the constellation of ___________, and it rises at ______ and sets at ______. Is it close to the ecliptic? ________.

13. **Use Right Ascension (α) and Declination (δ) to locate objects in the sky.** Astronomers use these coordinates to communicate positions in the sky; they work in the sky like geographical latitude and longitude work on the terrestrial globe. Open (double-click) the settings file called EquatorialGrid.vgr. In these settings the equatorial (α-δ) coordinate grid has been turned on. The concentric circles are like geographical latitude lines, the angle on them is declination (e.g. δ=50° declination); the radial lines are like geographical longitude lines, except that the readings on them are in hours (e.g. α =10° right ascension). Use the coordinate grid to
locate the star at right ascension $\alpha = 5^h 17^m$, declination $\delta = 46^\circ 00'$. Click on it; what is the star’s name? __________. Now turn the clock an hour or two worth. You’ll notice that the coordinate grid turns with the stars. So, how do your star’s coordinates change over time? __________.

Use the grid to read off Polaris’ coordinates: right ascension $\alpha =$ ____, declination $\delta =$ _____.

Next find the objects:
1. at $\alpha = 3^h 47^m$, $\delta = 24^\circ 07'$: __________, in the constellation of __________.
2. at $\alpha = 6^h 45^m$, $\delta = -16^\circ 43'$: __________, in the constellation of __________.

14. The Epoch. Find out what is at the origin of the coordinates, i.e. at $\alpha = 0^h 00^m$, $\delta = 0^\circ 00'$. To do this, navigate to the area and click the closest star you can find; Center it and zoom on it down to a $5^\circ$ view. Notice that the $\alpha = 0^h 00^m$, $\delta = 0^\circ 00'$ point, which is also called the vernal equinox, is the intersection of two lines that you have already met in this lab: the __________ and the __________. That is where the Sun is in the sky at the start of spring (March 21).

Now change to Star Atlas view (in the bottom left) and Lock on the star. Click the advance button on the time panel to jump one year ahead each time. You’ll notice that the vernal equinox actually moves over the years (this is due to precession, the change in the direction of the axis of Earth, mainly caused by the gravity of the Moon). By jumping 10 years’ worth (go from 2000 to 2010), you can read off from the data panel how much the right ascension changes in 10 years. You find ____ seconds per 10 years. For precisely telling the coordinates of a star (important not to confuse one faint star with another), you must tell the epoch (the year to which the coordinates refer). For example, if your star is HD 2 in Pisces, its coordinates are $\alpha = 0^h 05^m 03^s$, $\delta = -0^\circ 30'$ (2000.0) but $\alpha = 0^h 05^m 36^s$, $\delta = -0^\circ 27'$ (2010.0). The difference is $33^s$ and $3'$, which in arc minutes is $8'$ by $3'$. In an area of that size, even far from the Milky Way’s band, there are 13 stars of $14^m$ or brighter (visible in an amateur telescope) to mix them up. When you ‘buy’ a star and the “respectable seller” does not give you an epoch, you are scammed: you won’t ever know which star you have ‘bought’.

15. Quit SkyGazer by clicking -Q, then restart your computer.
Lab #6: Gravitational Acceleration

Gravity governs the motion of all the celestial bodies in the Universe, with the exception of the very rarified and hot interstellar gas (which feels magnetism as much as gravity). Gravity pulls everything down on Earth, it acts on the astronauts, it is pulling down the Moon, and it keeps Earth from escaping from the Sun into space.

It is quite remarkable that the acceleration caused by gravity is independent of the size, mass, or any other property of the body being pulled down. As counterintuitive as it seems, in the absence of air resistance, a feather and a hammer take the same time to fall down. A heavy hammer feels a stronger force of gravity but is also harder to move: the two effects exactly compensate each other. Any dropped object picks up the same speed at the end of a 1 sec long fall, about $9.81 \text{ m/s}$. The gravity of Earth accelerates a dropped object by this amount of speed every second; we say that the gravitational acceleration is $9.81 \text{ m/s}^2$.

This gravitational acceleration is due to the mass of Earth. We must imagine all of the mass of Earth concentrated in its center, which is $6,378 \text{ km}$ away from us (under our feet). Newton’s law of universal gravitation tells us that any mass pulls any other mass towards it, and the gravitational acceleration it causes is expressed by the formula

$$a = \frac{GM}{r^2}$$

where the universal gravitational constant $G$ has been measured in the laboratory, with the result of $G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg sec}^2)$. As you see from the formula, the gravitational acceleration depends on two things: (i) the mass of the gravitating object (Earth), and (ii) the distance from its center.

In this laboratory exercise we will measure the gravitational acceleration on the surface of Earth by dropping a ball and timing its fall, and then on the surface of the Moon by watching a video clip in which the astronauts drop objects on the Moon. We’ll look for visual proof of the fact that all bodies take the same time to fall, independent of their masses. We’ll use our results to calculate the masses of the Earth and Moon, and we will even be able to make a statement about the origin of the Moon!

The data we will need for this are:

- the radius of the Earth: $6,378 \text{ km}$.
- the radius of the Moon: $1,738 \text{ km}$.
- the average gravitational acceleration on Earth: $9.81 \text{ m/sec}^2$. (Compare with your result).
- Newton’s the gravitational constant: $G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg sec}^2)$.
- the distance to the Moon: $384,400 \text{ km}$.
PROCEDURE AND LAB REPORT

Date: ___ / ___ / 20__. Your name: ___________ Partner’s name: ___________ Section: __

1. Read the review, and to your instructor’s introduction, and answer:
   -- All astronomical objects move under the influence of gravity only, with the single exception of _____________________________________________________________.
   -- The effect of the Sun’s gravity on Earth is that Earth is _______________________.
   -- The strength of gravity is expressed by telling the ____________________________.
   -- Newton’s law of gravitation tells us that any object causes gravitational acceleration, by pulling other objects toward it, depending only on its ___ and _____________.
   -- Gravitational acceleration means what _____ a dropped object picks up every second.

2. Drop a tennis ball from a few meters high and time with a stopwatch how long it takes to reach the ground. Try it three times. Measure the height of the fall with a string and a ruler.
   -- The ball has been dropped from _________________, which is ________ m high.
   -- The ball took the following lengths of time in the three trials: ___ sec, ___ sec, ___ sec.
   Notice that the three values do not have to be exactly equal. There can be no measurement without an error margin! Round the numbers and keep as many digits as you can be sure are accurate. Average the three times; your result is ___ sec.

3. Calculate the average speed of the ball during the fall. Your result is ___ m/sec.

4. Calculate the gravitational acceleration. The ball is accelerating. Its average speed during the whole fall will be slower than its speed at the endpoint when it reaches the ground. You would expect (correctly) that the final speed of the ball was twice as fast as the average speed; that is, its final speed was ___ m/sec. This is how much speed the ball picked up during the whole time of the fall, so the gravitational acceleration has been measured to be ___ m/sec².

5. Compare this result to the theoretical value of 9.81 m/sec²; calculate the percent difference. Note that neither the theoretical nor your measured value is absolutely accurate; both have their corresponding error margins. We try to keep the errors low, but do not expect that any measurement can ever have no errors!
   The percent difference is _____ %; do you think this is acceptably low? ______________.

6. Now watch the clip on the “HammerAndFeather.mov”, which you’ll find in the folder Desktop/AstroLab/AstroDocuments. Repeat the above measurement and calculations by timing the hammer and feather dropped by the astronaut.
   -- The hammer took the following lengths of time in the three trials: ___ sec, ___ sec, ___ sec.
   -- Your estimate of the height of the fall is ________ m.
-- The average of the above times is ____ sec, the average speed is ____ m/sec, and the final speed is ____ m/sec, so the gravitational acceleration is found to be ____ m/sec².

7. From all this you conclude that (i) the hammer and the feather took ______ sec to fall down, and (ii) that the gravitational acceleration on the Moon is ____ times smaller than on Earth.

How high could you jump on the Moon? ______ m. A cow can certainly not jump over the Moon, but could you jump over a cow on the Moon? _____.

8. Given the above results, calculate the average density of the Earth.
-- The volume of Earth is \( V = \frac{4}{3} \pi r^3 = _____ \) m³. (Convert \( r \) to meters first.)
-- The mass of the Earth is \( M = _____ \) kg. (Solve \( a = G \frac{M}{r^2} \) for \( M \); you know \( a, G, \) and \( r \) now.)
-- The average density of Earth is \( \rho = \frac{M}{V} = _____ \) kg/m³ = ____ g/cm³.
-- Given that the density of water is 1 g/cm³, rock is \( \sim 2.5 \) g/cm³, and iron is 7.8 g/cm³, what is Earth primarily composed of? __________

9. Now do the same for the Moon.
-- The volume of the Moon is \( V = _____ \) m³.
-- The mass of the Moon is \( M = _____ \) kg.
-- The average density of the Moon is \( \rho = _____ \) kg/m³ = ____ g/cm³.
-- What is the Moon primarily composed of? __________

The correct answer indicates that the material that became the Moon could have been thrown out of the upper layers of Earth in a collision with another planet-in-the-making when Earth was still young.

10. Calculate the gravitational acceleration due to Earth at the distance of the Moon and estimate how much the Moon falls in a week’s time.
-- The distance to the Moon is ____ times larger than the radius of the Earth, so the gravitational acceleration should be _____ times weaker there; that is, _____ m/sec².
-- A week is _____ seconds, so at the end of a week, the Moon picks up _____ m/sec of final speed. The average speed is half of this, _____ m/sec, and in a week the Moon then falls _____ m = _____ km. So, how long would it take for the Moon to fall down? About _____.

11. Then, why does it not fall down? Because it also moves sideways.
-- In a week, the Moon travels _____ of its orbit, so it moves ______ km sideways. That puts it on an almost circular orbit.
Lab #11: The Mass of Jupiter

Galileo Galilei discovered the four largest moons of Jupiter in 1609, and they were named Io, Europa, Ganymede and Callisto. These moons provide an excellent way to illustrate Kepler’s III law about the speed of revolution, and they will be used in this exercise to determine the mass of the planet and to calculate its average density. This average density is the most important indicator of the internal composition of a planet, about which we cannot gain information in any other way. The basic idea is that the gravity of Jupiter determines the orbit of the moons, and gravity is caused by mass; so out of the motion of the moons you can tell the total mass of the planet.

Almost all work in astronomy starts with a long series of observations. A one-time look rarely tells us enough to understand much, but the two hours of a student laboratory are quite too short to do any sensible observation series. For this reason, we will use a computer simulator, part of the CLEA program developed by Gettysburg College, which shows Jupiter and its moons as you see them in a telescope at any time of your choice. You’ll be able to take a simulated “observation” and record the data. Another feature of astronomy is that the raw data means little in itself; new data is added to previous knowledge to produce one bit of additional knowledge at a time. You’ll follow this process; previous data will be given to you and you proceed to conclude on the internal composition of Jupiter.

Kepler’s third law in its modern form relates the time period $T$ of the revolution to the radius $a$ of the orbit (more precisely the semi-major axis) through $M \times T^2 = a^3$. This gives us the only way to determine the mass $M$ of celestial objects – provided they have a satellite whose orbit we can use. Jupiter has four large moons and Earth has one; we’ll measure each moon’s $a$ and $T$, and calculate the mass of the planet. The units in this form of Kepler’s law must be solar masses ($M_{\text{Sun}}$) for $M$, years for $T$, and astronomical units (AU) for $a$; you can convince yourself of the correctness of that by substituting in Earth’s orbit.

You will use the Julian Date (JD) for counting the number of days between two events. This JD is actually the number of days since 12:00 noon Universal Time on January 1, 4713 BC – an arbitrarily chosen time in the past, old enough to make sure that in all practical situations JD is a positive number. The usefulness of JD is that you can calculate the time that passes between two JD’s very simply: subtract the two dates to get the elapsed time in days. For comparison, think how hard it is to count how many days pass between, say, February 27 and August 12.

The incremental nature of astronomical knowledge requires previously determined data. Here are a few that you will need in this lab:

<table>
<thead>
<tr>
<th>Astronomical unit</th>
<th>Radius of Jupiter</th>
<th>Radius of Earth</th>
<th>Mass of the Sun</th>
<th>Length of year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1AU=149.6×10^6 km</td>
<td>71,492 km</td>
<td>6,371 km</td>
<td>2.00×10^{33} g</td>
<td>365.2425 days</td>
</tr>
</tbody>
</table>

Recall also that 1 km = 1000 m and 1 AU is the distance from the Sun to Earth.

**Note:** The purpose is to use your own (simulated) “measurements” to find the mass and density of Jupiter, so **do not use** any data other than that given in this worksheet!
PROCEDURE AND LAB REPORT

Date: __/ __/ 20__. Your name: ___________ Partner’s name: ___________ Section: __

1. **Start up the computer in Windows XP.** If it is running MAC, you will have to restart it while holding down the **OPTION** key. Use the **Student** account to log in.

2. **Read the introduction,** then answer these questions:
   (i) What numbers do you find on the two sides of Kepler’s III law, when you substitute in Earth’s orbital data? Which object’s mass is $M$ then? ____________________________
   (ii) What is the only way to determine the mass of a planet? ____________________________
   (iii) Why is JD used in astronomy instead of date and time? ____________________________

3. **Start up the simulation** (click Desktop→AstroLabs→MassOfJupiter→CLEA). Use File→Log In to insert your names (one or two students in a group), and select the Revolution of the Moons of Jupiter option. Click File→Run.

   Use these settings (under File):

<table>
<thead>
<tr>
<th>Magnification</th>
<th>100 ×</th>
</tr>
</thead>
<tbody>
<tr>
<td>Features</td>
<td>Animation, Use ID Color, Show Top View</td>
</tr>
<tr>
<td>Timing</td>
<td>Obs. Steps: 0.1 h</td>
</tr>
<tr>
<td>Observation Date</td>
<td>Today’s date. Set time to 00:00:00 by deleting the time altogether.</td>
</tr>
</tbody>
</table>

   Place the **Top View** next to the main panel, so they do not overlap. Set the **View** on the **Top View** panel at: Large, Show Orbits, Show eclipse zone, and Eclipses → Show Eclipsed Moon As “+”, and do not later change these top view settings at all.

4. **Start the animation** (press **Cont.**) and observe what is happening. Notice that the outer moons move more slowly than the inner ones. Change the magnification. Notice that the moons pass in front of or behind Jupiter, and that they cast a shadow on Jupiter sometimes. Stop the animation when a moon approaches Jupiter, and proceed step-by-step. (Keep clicking **Next.**) Using the display of the time (UT), determine how long it takes for the moon to pass in front of Jupiter. Click on your moon to reveal its name. Your answer is:

   On __/__/ __, the moon __________ took __ h __ m of time to pass in front of Jupiter.

   Notice that the moons either do not show immediately after they pass behind Jupiter, but appear suddenly later or they suddenly vanish before hiding behind the planet. They in fact are eclipsed: that is, they go into Jupiter’s shadow. This shadow is the region between the two green lines. Follow one of the moons through an eclipse. By proceeding step-by-step again, determine the time of the vanishing/reappearance of a moon from the shadow. You found that:

   On __/__/ __, the moon __________ vanished/reappeared (circle which) at __ h __ m.
When a moon goes farthest on one side from Jupiter, it is called an elongation event. The moon’s distance from Jupiter will be equal to the radius of the moon’s orbit. Run the animation and stop it close to maximum elongation of a moon on the right side (West), and click on the moon to tell how far to the right it is from Jupiter, in units of the diameter of Jupiter’s disk. On ___ / ___ , at __ h ___ m UT, the moon __________ was ____ $D_{Jup}$ in western elongation.

5. Use these settings (this will slow the animation):

<table>
<thead>
<tr>
<th>Magnification</th>
<th>100 ×</th>
</tr>
</thead>
<tbody>
<tr>
<td>Features</td>
<td>Animation, Use ID Color, Show Top View</td>
</tr>
<tr>
<td>Timing</td>
<td>Obs. Steps: 0.01667 h</td>
</tr>
<tr>
<td>Observation Date</td>
<td>Today’s date. Set time to 00:00:00 by deleting the time altogether.</td>
</tr>
</tbody>
</table>

Measure time of two adjacent eastern elongations of each of the four moons, and record them in the table. (You’ll need to go step-by-step when the elongation approaches, because the animation is too fast and you cannot run backwards. If you skip the elongation, set the “Observation Date/Time” back. You may change the observation steps if you find it more convenient.) Read off the elongation distances, too, and record them in the table. At this stage you’ll have filled out the shaded portion of the table. Change the magnification as convenient.

*In all your calculations, keep 2 decimal digits only!*

<table>
<thead>
<tr>
<th></th>
<th>1st elong.</th>
<th>2nd elong.</th>
<th>Elongation distance (a)</th>
<th>Revolution time (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day &amp; Time</td>
<td>JD 245...</td>
<td>Day &amp; Time</td>
<td>JD 245...</td>
</tr>
<tr>
<td>Io</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ganymede</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Callisto</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moon</td>
<td>- - -</td>
<td>- - -</td>
<td>- - -</td>
<td>- - -</td>
</tr>
</tbody>
</table>
6. Calculate the remaining entries in the table below. You will need the data from the explanation above. Use scientific notation for numbers that are too small or too large.

<table>
<thead>
<tr>
<th>Unit</th>
<th>$a^3$</th>
<th>$T^2$</th>
<th>$M_{\text{planet}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>$\times 10^9$</td>
<td>$\times 10^6$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Europa</td>
<td>$\times 10^9$</td>
<td>$\times 10^6$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Ganymede</td>
<td>$\times 10^9$</td>
<td>$\times 10^6$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Callisto</td>
<td>$\times 10^9$</td>
<td>$\times 10^6$</td>
<td>$\times 10^4$</td>
</tr>
<tr>
<td>Moon</td>
<td>$\times 10^9$</td>
<td>$\times 10^6$</td>
<td>$\times 10^4$</td>
</tr>
</tbody>
</table>

7. Kepler’s III law, $M \times T^2 = a^3$, predicts that the mass of Jupiter calculated from $M = a^3 / T^2$ should be the same, no matter which moon you are using for the calculation. They won’t be, because any measurement involves an error, though preferably a small one. (This is not the same thing as human error, which is simply doing it wrong!) To minimize this measurement error, calculate the average of the masses you found. After converting solar masses to kilograms, you conclude that the mass of Jupiter is: $M_{\text{Jup}} =$ ________$M_{\text{Solar}} =$ ________$g$. The same calculation, for comparison, tells the mass of Earth: $M_{\text{Earth}} =$ ________$M_{\text{Solar}} =$ ________$g$.

8. Out of your measured values of Jupiter’s and Earth’s masses you can now calculate the density of each. First, use the volume of a sphere, $V = 4\pi R^3 / 3$, to calculate the volume of both planets. (Make sure you have converted $R$ to centimeters!) Show your results: $V_{\text{Earth}} =$ ________$cm^3$; $V_{\text{Jup}} =$ ________$cm^3$. Then, calculate the density of both planets, $\rho = M / V$. (Make sure you have converted $M$ to grams!) Show your results: $\rho_{\text{Earth}} =$ ________$g/cm^3$; $\rho_{\text{Jup}} =$ ________$g/cm^3$.

9. Given that the density of water is $\rho_{\text{water}} = 1 \text{ g/cm}^3$, and the density of rock is about $\rho_{\text{rock}} \approx 3 \text{ g/cm}^3$, what can you tell about the composition of Earth and of Jupiter? (Do not forget that the center of each planet must be much denser than the outside!) Explain:

10. **Review:** Looking at your table, how many different nights did you have to ‘observe’ the moons of Jupiter to collect the data? How many hours of observation do you think you would have needed each of these nights? Explain why.

11. **Extra credit:** The masses and densities that result from this experiment are somewhat too low. What do you think has been overlooked that causes such error?
Lab #13b: Distance to the Moon (Daily Parallax)

PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: __________ Partner’s name: __________ Section: __

Read:
In the laboratory we’ll use the daily parallax of the Moon to determine its distance. First, you’ll look at two pictures of the Moon taken on Sept. 5, 2004, when the Moon passed close by the Seven Sisters. You’ll determine how fast the Moon was moving and calculate how fast it should be moving due to its monthly orbital motion. There will be a discrepancy, which you’ll calculate. The discrepancy is due to the fact that we are watching the Moon from a spinning Earth and we are in fact moving quite fast, from West to East. We’ll calculate how fast we are moving, and relating that to the discrepancy this difference is supposed to explain, we’ll find the distance to the Moon.

Procedure:
(1) Look at the two pictures. The stars have turned in the two hours between the times when they were taken, and the Moon has also moved in relation to the stars. The easiest way to determine this motion is to place a sheet of tracing paper over your pictures and copy the stars and the two positions of the Moon on the same sheet. Each time, align the stars with each other. Notice the faint star on the bottom of the picture: it will help you to find the precise alignment of the two pictures. Now, on the tracing paper, you will see how much the Moon has moved. Measure the distance with a ruler: _____ mm. Now, you will need to find out how many degrees this movement corresponds to, and the easiest way to do that will be to compare it to the known size of the Moon. Measure the diameter of the Moon in the picture: _____ mm. From this, knowing that the diameter of the Moon is in fact 0.5 degrees, you conclude that the Moon has actually moved _____ degrees in two hours, which is _____ degrees per hour.

(2) Now calculate how much the Moon was supposed to move due to the fact that it revolves around Earth. In 27.322 days it makes a full circle (360 degrees), so it moves _____ degrees a day, so _____ degrees per hour.

(3) Now calculate the discrepancy between how fast the Moon is supposed to move and how fast it actually moves. If you did the calculation correctly, it will actually be moving slower than it is supposed to move. The difference is _____ degrees per hour. At this rate, it takes $t = _____ hours$ for the difference to become a half a degree.
(4) This difference is due to the fact that we are watching the Moon from a spinning Earth. In fact Earth is rotating West to East one turn a day. The length of the equator is 40,000 km, so the speed of spin of a point on the equator is 40,000 km / 24 hours = _____ km/h = _____ mph. Mississippi, being north of the equator, moves with 82.51% of this speed, which is _____ km/h.

(5) With this speed, in \( t = \) ___ hours (copy!) Mississippi moves a distance of \( x = \) ___ km, and the discrepancy becomes a half a degree. We know that anything that looks a half a degree in size is a 100 times farther than its size, so we conclude that the distance to the Moon is \( 100 \times x = \) ______ km.

(6) Is your result reasonably close to the actual distance to the Moon, which varies from 369,600 km to 404,500 km? Is this a precise method to determine the distance to the Moon? _____________________________________________________________
_______________________________________________________________________

These pictures were taken with an \( f=180 \) mm telephoto lens at \( f/8 \), piggybacked on an equatorially mounted LX200 telescope, on regular 100 speed film (24 mm x 36 mm). A careful examination might even detect the inaccuracy of the tracking. Notice the star in the bottom of the picture!
Lab #13c₂: Distance to the Moon (Apparent Size 2)

The distance from us to the Moon changes during the day as the Moon rises high up in the sky, as indicated on Fig. 1. This results in the Moon appearing to be somewhat *smaller* when it is rising, contrary to everyday perception. The difference can be measured in a photograph and can be used to determine the distance to the Moon, provided we know how large Earth is.

The two separately supplied laminated photographs of the Moon were taken October 27, 2004 by an amateur astronomer in Monterey, CA. The first one was taken of the eclipsed Moon at 7 pm, just after moonrise, the other one was taken at 11 pm when the Moon was high up in the sky. Comparing the size of the Moon on the two pictures, we can tell how far the Moon is.
A disturbing effect is what is called refraction. Light entering our atmosphere will be turned from its original direction. Any point on the Moon will appear to be higher up in the sky than it really is by as much as a half a degree (Fig. 2). In addition, the bottom of the Moon is "raised" less than the top, and the shape of the Moon is distorted. The rising Moon looks as if someone hit its top and the vertical size is changed. In order to avoid the error this effect introduces into your measurement, you'll need to measure the horizontal diameter of the Moon, which is not affected by refraction.

Fig. 2. Refraction: the rising Moon appears higher up from where it really is.
PROCEDURE AND LAB REPORT

Date: __/ __/ 20__. Your name: __________ Partner’s name: __________ Section: __

A. Read the review.

B. Follow the steps of the calculation:

(1) On the two pictures supplied, measure the size of the Moon with a ruler. You will need to do this very accurately, with the precision of a tenth of a millimeter. Your results are: the Moon is _____ mm in diameter on the picture when it is 67° up, and _____ mm in diameter on the picture when it is 6° up.

(2) Now calculate the difference. The Moon is _____ mm larger when it is high up. This is _____% of its diameter. The Moon is this many percent closer when it is high up.

(3) With a good approximation, the Moon is one Earth radius, 6340 km, closer to us when it is high up. Out of this, calculate the distance to the Moon: ______ km.

(4) Compare this result with the actual distance to the Moon, measured more accurately through the time delay of radio signals, to be 384,400 km. How accurate is your result, and what do you think is the main reason for the difference?

____________________________

(5) For a bonus point: Measure the percent change refraction causes in the apparent size of the Moon. Show your calculation below.
How do we know what the stars or the Sun are made of? The light of celestial objects contains much information hidden in its detailed color structure. In this lab we will separate the light from some sources into constituent colors and use spectroscopy to find out the chemical constitution of known and unknown gases. The same procedure is used for starlight, telling us what its source is composed of. The baseline is a laboratory experiment with known materials, and later we can compare the unknown to what we already know.

Hot, glowing bodies, like a light bulb or the Sun, glow in all the colors of the spectrum. All these colors together appear as white light. When such white light hits a prism, a raindrop, or a diffraction grating, the colors get separated according to their wavelengths. Red, with its wavelength of 600 nm to 700 nm, is deflected least and ends up on one edge of the spectrum. Blue, with a wavelength around $400\text{ nm}$, is at the other end of the visible spectrum. An infinite number of elementary colors are located between these two edges, each corresponding to its own wavelength. When sunlight hits raindrops after a storm, the spectrum shows up in the sky as a rainbow.

An incandescent light bulb radiates a continuous spectrum. All colors are present in this “thermal glow”, and it is impossible to tell what the chemical composition of the source is. However, other physical processes produce different spectra. A fluorescent light tube works, crudely speaking, on the principle of lightning. Electrons rush from the negative pole to the positive pole inside and hit gas atoms in the tube, making them emit light. This sort of light contains only a few colors and is called an “emission spectrum”. When we separate the colors
of such light, only a few bright “emission” lines appear, each in its own color (and wavelength). Each sort of atom will emit light at its own particular set of wavelengths. When we analyze the emission spectrum of an unknown source, we can compare the colors of its spectral lines to known spectral lines we see in a laboratory and tell which substance matches.

**Having read this much,** please open the file *SpectroscopyQuestions_1.pdf* in the folder *Desktop/AstroLab/AstroDocuments*. Your instructor will tell you **which set of three** questions to answer. **Put down the answers** in the space provided below to Questions 1-2-3.

The color of spectral lines is directly related to the structure of the atoms. Electrons can jump from one orbit around the atomic nucleus to another, giving off the difference in energy levels in the form of light. The wavelength (color) of light is inversely proportional to the amount of energy freed up between the old and the new orbit. In the case of hydrogen, there is a simple formula, which tells us the wavelength of the spectral lines, called the **Balmer formula**:

$$\lambda = \frac{91.177 \text{nm}}{\left(\frac{1}{N^2} - \frac{1}{n^2}\right)}$$

This tells the wavelength associated with an electron jumping from the N\textsuperscript{th} to the n\textsuperscript{th} orbit (or backwards). The “Balmer series” spectral lines, which we will measure, called H\textalpha, H\textbeta, H\textgamma, etc., correspond to the electron jumping from some level n=3,4,5,… down to levels N=2. (Of course, hydrogen has another series of spectral lines, the Lyman series, which corresponds to N=1, but they are not visible to the human eye.)

In this laboratory we will measure the wavelengths of spectral lines from a few gases, which are easy to put inside a discharge tube. Other chemical elements would have different spectra, and the details of these spectra also contain information on the temperature, pressure, gravity, speed of motion, and much else inside the source of light. We will apply what we learn here to the study of spectra of stars in a later laboratory exercise.

In the spectroscope that we use in this laboratory, there is a diffraction grating (many parallel black lines drawn very tightly on a little piece of film). It breaks up the light entering through the input slit into colored lines. Each color corresponds to a wavelength, measured in nanometers (nm). Note that 1 nm = 10\textsuperscript{-9}m = 1/250 of a millionth of an inch, a very small unit. The wavelength of visible light is very short indeed.

**Having read this much,** please open the file *SpectroscopyQuestions_2.pdf* in the folder *Desktop/AstroLab/AstroDocuments*. Your instructor will tell you **which set of three** questions to answer. **Put down the answers** in the space provided below to Questions 4-5-6.
The view in the spectroscope

Top view of the setup

Tube holder
Discharge tube
Flashlight to illuminate scale
Light in
Aim
Spectroscope
Grating
Light out
Eye

Scale to use (nm)
Input slit

A diffraction grating breaks up mixed colors into constituents
Light in - white
Grating
Light out - spectrum
PROCEDURE AND LAB REPORT

Date:__/__/20__. Your name: ___________ Partner’s name: ___________ Section: __

IMPORTANT NOTE: Keep the tube switched off at all times except for the 30 seconds while you are looking into the spectoscopes!

(1) Listen to the introduction by your instructor.
(2) Read the first half of the Introduction and answer the three questions in the space provided below.
(3) Read the second half of the Introduction and answer the three questions in the space provided below.
(4) Examine your spectroscope and identify its parts:
   -- Find the opening where light enters. Find the grating and find out how to turn it around. Find out how to aim the spectroscope at a light source.
   -- Look into the spectroscope. You’ll need to use your glasses or contacts (if any) to see the scales clearly. You will use the wavelength scale (it goes from 400 nm to 700 nm) to read off the wavelength of spectral lines.
   -- Hold the spectroscope in your hands and aim at a fluorescent light. You’ll see the input slit light up on the right (see the picture!). Grab the edges of the grating just under and above the viewing hole to align the grating, so that the spectral lines you see are exactly vertical. If the grating is positioned at the wrong angle, you may not see any spectrum at all.
(5) At this point the ceiling lights will be switched off; plug in the incandescent lamps.
(6) Assemble the setup as shown in the picture. Insert a hydrogen discharge tube into the socket. Handle the tubes carefully, because they are fragile and expensive! Do not touch the tubes with bare hands: the grease on human hands may cause the tubes blow up, so use gloves or a paper towel to touch them. Make sure the power supply is switched off to avoid an electric shock! Make sure that the spectroscope is stable enough on its holder and that the opening that accepts light aims straight at the middle of the tube. Simply holding the spectroscope in your hands and aiming it at the source will be unlikely to work.
(7) Aim the spectroscope at the discharge tube. First the input slit should light up; make it as bright as possible by aiming carefully. You should now see a few spectral lines (the grating might need a little readjustment at this point). Read off the wavelengths of the three or four bright hydrogen lines (these will be, from red to blue, Hα, Hβ, Hγ, and possibly Hδ) and record them in your report. If the scale is too dark, you may shine some light into the broad opening on the front left of the spectroscope to illuminate it. Using a color pencil, draw the lines in your report as you see them (spectrum #1).
(8) Using the Balmer formula with N=2 and n=3,4,5,6 calculate the wavelength of each of the lines as predicted by theory and insert your calculated prediction into the table in your report. Calculate the percent error – the difference between theory and experiment. You should expect a 1-2% error. Note that no measurement can ever be absolutely precise, there is always some error.
(9) Replace the hydrogen tube with another discharge tube filled with known gases three more times. (Careful, the tubes are hot!) Draw a few of their brightest emission lines as you see them (spectra #2-3-4). Use color pencils. With the aid of the laminated spectra, check that the tube contains the correct gas.

(10) Take a “mystery” tube that is not labeled with a name, but only with a number. Draw the spectrum of the gas in it, and identify the gas. Use two tubes per student, i.e. four per group. (spectra #5-6).

(11) Aim the spectroscope at an incandescent light bulb. Observe that no spectral lines are visible, but you see all colors of a full spectrum instead. Thermal glow produces a continuous spectrum.

(12) Aim your spectroscope at a fluorescent light again. Draw the spectrum as you see it (spectrum #7). Try to identify the bright spectral lines with the laminated spectral charts. What gas or gases are there in the light tube? In case your light bulb has a spectrum that is different from all those in the chart, explain why. (Answer #7 below.)

**Drawings of Spectral Lines and Identification of Gases**

<table>
<thead>
<tr>
<th>Spectrum #1</th>
<th>Gas: Hydrogen</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Spectrum #2</th>
<th>Known gas:</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Spectrum #3</th>
<th>Known gas:</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
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<th>Known gas:</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Spectrum #5</th>
<th>Unknown gas:</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Spectrum #6</th>
<th>Unknown gas:</th>
<th>Number of tube:</th>
<th>700 nm</th>
<th>600 nm</th>
<th>500 nm</th>
<th>400 nm</th>
</tr>
</thead>
</table>

| Spectrum #7 | Fluorescent light | Gas(es) it contains: | 700 nm | 600 nm | 500 nm | 400 nm |
Questions answered:

Set ____

1.: _______________________________________________________________________

2.: _______________________________________________________________________

3.: _______________________________________________________________________

Set ____

4.: _______________________________________________________________________

5.: _______________________________________________________________________

6.: _______________________________________________________________________

7. (About the fluorescent light): _______________________________________________________________________

---

Measured and predicted wavelengths of hydrogen lines

<table>
<thead>
<tr>
<th>Name of line</th>
<th>Transit</th>
<th>Predicted $\lambda$ [nm]</th>
<th>Measured $\lambda$ [nm]</th>
<th>Color</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$\alpha$</td>
<td>from $n=3$ to $N=2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$\beta$</td>
<td>from $n=4$ to $N=2$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_-$</td>
<td>from $n=___$ to $N=__$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H$_-$</td>
<td>from $n=___$ to $N=__$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Lab #15b: Magnitudes, the Hertzsprung-Russell Diagram, and Distances

The Hertzsprung-Russell diagram is an important tool in the study of stars. In the early 1900’s the two astronomers investigated nearby stars and found a relationship between their color and brightness. This work lead to the important discovery that the brightness of a star is related to the temperature of its surface. In the typical HRD the absolute magnitude (brightness) is plotted against the spectral type (temperature or color) of a star. The HRD for this lab shows several different types of stars and their proper names, including the Sun.

**Here are some important definitions for terms used in the lab:**

**Apparent magnitude** – The measure of the brightness of a star as seen from Earth.

**Absolute magnitude** – The measure of the brightness of a star as it would be seen from the standard distance of 10 parsecs. A parsec (pc) is a unit of distance; 1 pc = 3.26 light years.

**Spectral type** – Indicates the color of the star, which is related to its surface temperature. From the hottest to coolest, and from blue to red color, the types are: O, B, A, F, G, K, M. A second number is added for finer classification, like G0, G1, G2, …, G9. A blue star is hotter than a yellow star, which is hotter than a red star.

The apparent magnitude of a star can be directly measured, because it indicates how bright the star looks in the sky. From the distance of 10 parsecs, a star would look fainter or brighter than from Earth, depending on its actual distance. The difference between a star’s absolute and apparent brightnesses tells its distance from us. The mathematical relationship is:

\[ M = m + 5 - 5 \log d \]

where \( \log \) is 10-based logarithm and
- \( M \) is the star’s absolute brightness,
- \( m \) is the star’s apparent brightness,
- \( d \) is the distance to the star in parsecs.

Using the HRD and other information, you will determine the distances to various stars and compare various stars with each other. Notice that you’ll need to solve the above equation for \( d \); to simplify matters we did it for you: \( d = 10^{\frac{m-M}{5}} \).

**The main sequence** – The line on the HRD where most (but not all) stars are located. Main sequence stars “burn” hydrogen into helium to produce heat; giants burn helium into heavier elements; white dwarfs have no active source of heat in their cores any more.
PROCEDURE AND LAB REPORT

Date:__/__/20___. Your name: ___________ Partner’s name: ___________ Section: __

1. Examine the HR diagram. Find the spectral type and absolute magnitude of the stars in the table. (Those not yet on the HRD will be filled in later.)

<table>
<thead>
<tr>
<th>Name</th>
<th>Official name</th>
<th>Spectral type</th>
<th>Color</th>
<th>Distance (light years)</th>
<th>Absolute magnitude</th>
<th>Apparent magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirius A</td>
<td>α Canis Maioris</td>
<td>-</td>
<td></td>
<td>1.4 ly</td>
<td>-1.4</td>
<td>-27.0</td>
</tr>
<tr>
<td>The Sun</td>
<td>-</td>
<td>-</td>
<td></td>
<td>= ly = 27.0 km</td>
<td>-27.0</td>
<td></td>
</tr>
<tr>
<td>Betelgeuse</td>
<td>α Orionis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rigel</td>
<td>β Orionis</td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Proxima</td>
<td>α Centauri C²</td>
<td></td>
<td></td>
<td></td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>Alcyone</td>
<td>η Tauri in the Pleiades</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Procyon</td>
<td>α Canis Minoris</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The G2 star in # 5</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Cross out the wrong words, leaving the correct answer:
   - Based on its position in the HRD, Proxima is hot or cool and bright or faint.
   - Based on its position in the HRD, Betelgeuse is hot or cool and bright or faint. That makes it a red or blue giant or dwarf.
   - Based on its position in the HRD, Rigel is hot or cool and bright or faint. That makes it a red or blue giant or dwarf.
   - Sirius is a double star. The very bright Sirius A is accompanied by a faint one, called Sirius B.
     Based on its position in the HRD, Sirius B is hot or cool and bright or faint. That makes it a red or white giant or dwarf.

3. Use the formula relating the absolute and apparent magnitudes with the distance to determine how far Procyon (α Canis Minoris) is.
   - Procyon’s apparent magnitude is \( m = 0.35 \text{ mg} \), so it is a very bright, bright, faint, very faint star.
   - Its absolute magnitude is \( M = \text{mg} \). This means that from a distance of 10 parsecs it would look much brighter, brighter, fainter, much fainter than from Earth.
   - This means that it must be much farther, farther, closer, much closer than 10 parsecs.
Your solution of the equation is \( d = \text{parsecs}, \) which is indeed much farther, farther, closer, much closer than 10 parsecs. Convert the distance to Procyon to light years; \( d = \text{light years}. \)

4. Use the above procedure to determine how far the following stars are:
   - Betelgeuse \((m = 0.45 \text{ mg.})\)
   - The Seven Sisters (Alcyone, a B4 main sequence star, is \( m = 2.87 \text{ mg}. \))

Plot them in the HRD and fill in the table entries.

Answer: Betelgeuse: \( \text{parsecs} = \text{light years} \), the Pleiades: \( \text{parsecs} = \text{light years} \).

5. Suppose an observer finds a faint, \( m = 13 \text{ mg} \) yellow main sequence star in the sky, similar to the Sun (spectral type G2). How far is it? Where is it on the HRD?

Answer: \( \text{parsecs} = \text{light years} \). In which part of the Galaxy can that star be?

This star will be outside the Galaxy, or in the other end of the Galaxy, or somewhere halfway though the Galaxy, or in the Solar neighborhood. Recall that the Galaxy is 30,000 parsecs in diameter.
Lab #18a: Hubble’s Law

The single most important discovery about the structure of the Universe, made in the early 1920s, was that the Universe is expanding. This fact implies the Big Bang, some 14 billion years ago. Edwin Hubble, an American astronomer working at Mt. Wilson observatory in California in the 1920’s, established that the recession velocity of galaxies (that is, the speed of expansion) is proportional to their distance. This relationship is now called Hubble’s Law, and the constant of proportionality is called Hubble’s constant. The reciprocal of Hubble’s constant is nothing else but the age of the Universe (since the Big Bang).

Far-away galaxies move away from us with high speed then. This motion can be detected with spectroscopy: the lines in the spectra of galaxies are shifted towards the red (the Doppler effect). The amount of redshift will tell us how fast each galaxy is receding. Hubble’s law relates this to the distance to the galaxy. It is quite difficult to precisely measure the distance to a galaxy, and here is the hard part of setting up Hubble’s Law.

In this laboratory exercise we will see the simplest, although not very accurate proof of Hubble’s law. Essentially, we will repeat Edwin Hubble’s original discovery, but we will use much more spectacular pictures (taken by the Hubble Space Telescope) and much more precise and detailed spectra (taken by the Sloan Digital Sky Survey, SDSS for short, in New Mexico).

The essence of our work (in Part 1) will be to establish Hubble’s Law, the relationship between redshift \( z \) and the distance \( d \) of a few galaxies,

\[
v = H \times d
\]

where \( H \) is the Hubble constant. We’ll take the redshift from the spectra. Astronomers use the relative change in the wavelength of a spectral line to describe the amount of redshift, \( z = \frac{\Delta \lambda}{\lambda} \), which then equals the speed of recession relative to the speed of light. For not too large speeds this will mean \( z = \frac{v}{c} \). It will be easy to read off \( \Delta \lambda \) and \( \lambda \) from SSDS spectra with decent precision.

The hard part is to tell the distance to our galaxies. We will follow a quite visual, but not very precise method to tell how far a galaxy is: a far-away galaxy looks smaller than a close-by one. Of course, we need to assume that all these galaxies are the same size as our Galaxy (about 100,000 light years across.) This is not quite right; and this will be the main source of error in our results. It is remarkable though, that even with such a crude assumption, we still get a reasonable approximation to Hubble’s Law.

We have a few pictures of galaxies taken by the HST. For your convenience, there is a scale indicted on each; the scale is in arc seconds (as), the unit of apparent size of an object in the sky. You’ll take a 100,000 light year (=30,000 pc) sized galaxy and measure its apparent diameter in arc seconds.
The apparent size will be related to its true size though the simple relation $D = d \times \theta$, where $D$ is the diameter of the galaxy, $d$ is the distance to it, and $t$ is its apparent size. This is nothing more sinister than the length of the arc of a circle that you might remember from 7th grade, indicated on this picture, with the angle $\theta$ in radians:

![Diagram showing the relationship between the diameter of a galaxy, its distance, and its apparent size.](image)

When you convert from radians to arc seconds, you find $D = d \times \theta[\text{arc}]/200,000$ simply because a radian is about 200,000 arc seconds. We are assuming that our galaxies are $D=30,000$ pc across, so our formula for finding the distance to a galaxy $d = \frac{6,000\text{Mpc}}{\theta[\text{arc}]}$ comes out in megaparsecs (1Mpc=1 million parsecs). You will estimate how large the galaxy looks on the pictures in arc seconds and calculate how far it is using this relation.
PROCEDURE AND LAB REPORT

Date: __/ __/ 20__. Your name: __________ Partner’s name: __________ Section: __

To make sure you understand, and you know what you are doing, answer the following questions.

1. In the expression for redshift, what do \( \Delta \lambda \) and \( \lambda \) mean?
   \( \Delta \lambda: \quad \) _____________________ ; \( \lambda: \quad \) _____________________

2. \( d = \frac{6.000 \text{ Mpc}}{c \theta_{(\text{as})}} \) means that the farther a galaxy is the _____ it looks.

3. \( z = \frac{\nu}{c} \) means that the more redshifted a galaxy is the _________________.

4. How many light years is a Mpc? __________________________

Determine the apparent size, then the distance of each galaxy in the pictures.
(Here, NGC stands for “New General Catalog”, “Arp” is a catalog compiled by Halton Arp, and “COSMOS” is a collaboration based on the Hubble Space Telescope.)

Look at each picture and read out how large, compared to the indicated scale, each galaxy is. Enter the answers in the table.

Note these peculiarities: #1. COSMOS3127341 and Arp148 look small, so they are far away. The full extent of these galaxies is larger than they look at first sight. #2. NGC 4911 has a large, faint halo, which extends to farther than the size of a normal galaxy: do not include all of this halo into the diameter of the galaxy. #3. NGC 5584 looks as if it did not completely fit in the picture; estimate its diameter a little larger than it looks in the picture.

Next, calculate the distance to these galaxies. Enter your results in the table.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Apparent size [as]</th>
<th>Distance [Mpc]</th>
<th>H(_\beta) line [nm]</th>
<th>H(_\alpha) line [nm]</th>
<th>( z )</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3434</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
<tr>
<td>NGC 4911</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
<tr>
<td>NGC 5584</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
<tr>
<td>COSMOS3127341</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
<tr>
<td>Arp 148</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td>( \lambda_{\text{galaxy}} )</td>
<td>( \Delta \lambda )</td>
<td>( z )</td>
<td></td>
</tr>
</tbody>
</table>
Determine the redshift, then the recession speed of each galaxy in the pictures.

Examine the SDSS spectra in the posters. The poster shows three spectra; the middle one is the spectrum of the galaxy in true colors. Notice that some spectral lines are dark (absorption lines from starlight), and others are bright (emission lines from interstellar gas). There is also a black-and-white version of the same (galaxy) spectrum on the top, for easier viewing, and also a spectrogram, which is nothing else but the spectrum turned into a graph.

The bottom spectrum, on black background, is the spectrum of hydrogen as you have already seen in the Spectroscopy lab.

Look at the spectrum of NGC 3434 now. You’ll notice that this galaxy has a bright H\textsubscript{\beta} line (H\textsubscript{\beta} in emission), and it is redshifted. The same is true of the H\textsubscript{\alpha} line. But there are additional lines in the spectrum of the galaxy, and we have to make sure that we do not misidentify them. A look at the H\textsubscript{\gamma} and the H\textsubscript{\delta} lines convinces you that they are similarly redshifted, so they have not been confused with some other lines.

Now, you are ready to read off the wavelength of the spectral lines for each galaxy. Try to estimate the wavelengths to one decimal precision, and insert them into the table.

Your next job is to calculate the redshift of each galaxy using the relations that you learned in the introduction. Keep three decimals and insert your numbers for z in the table.

You will have two values of z for each galaxy. If they do not match within reasonable error, you either made a mistake in the calculation or confused the lines and have to correct it.

Make the Hubble plot.

Use the provided graph paper with the scale on it. Include all the five galaxies, mark which one is which, and include our Galaxy (you know its d and v, right?)

Finally, connect the six points with a straight line. You want the line to cross exactly through the origin. If drawing a straight line seems possible within reasonable error, then you know Hubble’s law is correct.

Determine the Hubble constant and the age of the Universe.

The Hubble constant is the slope of your straight line in the Hubble plot. To calculate it, read off the recession velocity of a galaxy that would be at 500 Mpc distance: _______ km/s. Calculate H = v/d = (_________km/s) / (500Mpc) = _____ km/s/Mpc.

We now calculate the size and the age of the Universe. Take an extreme object receding with the speed of light: it would be as far as the size of the Universe. Hubble’s law says for it c=H\times d, which we solve as d=c/H=300,000km/s / (_____ km/s/Mpc ) = _____ Mpc = __ billion ly. As light goes one light year a year, we conclude that the Big Bang happened ______ years ago.
Notice that astronomy is a mathematical science: You are doing (very simplified) calculations to determine things like the age and size of the universe; or in the next section, to determine the nature of a galactic nucleus. Without the math, you would get nowhere: the quasar could have been a planet or the Universe could have been as young as a few thousand years old; you would not understand anything about the world you live in.
**Apply Hubble’s law to a quasar.**

Now that you have set up Hubble’s law, you are ready to use it the way astronomers usually do. They take the spectra of all sorts of galaxies, determine the redshift, and read off the distance to the object from the Hubble plot. You will be doing this with the brightest quasar in the sky, known as 3C273 (the 273rd object in the 3rd Cambridge catalogue of radio sources), and find some rather astonishing conclusions.

This object, a known radio source, looks like a nondescript 13-magnitude star in the sky. (Look at its Sloan picture on the left of its poster.) It is a variable star that changes its brightness by a half a magnitude within hours, proving that it cannot be much larger than a few astronomical units, which is not surprising for a star at all.

The spectrum of this “star” reveals the true surprise: its spectral lines are hugely redshifted. Check it yourself: measure the redshift of the Hα and Hβ lines the same way as you did with the galaxies; fill out the values for \( \lambda, \Delta \lambda, z, \) and \( v \) in the table below. The huge speed indicates that this object cannot be part of the Galaxy: it moves away much faster than the escape velocity from the Galaxy (which is \( \approx 500 \) km/s). But then it must be an extragalactic object, and the redshift must follow Hubble’s law.

![Table](image)

Once you reach this conclusion, you can use your Hubble diagram to tell the distance to 3C273. Do that: indicate its position on your graph, read off its distance and insert it into the table. Obviously, you find that is farther than any of the five galaxies that you studied previously.

Because you have established that this quasar ("quasi-stellar radio source") is very distant, you may suspect that it might have to be something like another galaxy. Yes and no: a more detailed Hubble Space telescope image (the middle one in the poster) detects no galaxy, and no spiral structure, but only the bright star and a jet flying out of it. However, on the right panel in the poster they used a "coronograph" on the space telescope: they placed a small black disk in the way to block out the 13mg bright star. And indeed, the star gone, the faint haze of a galaxy is revealed around the blocked-out star. To check that this is correct, estimate the diameter of this galaxy in arc seconds, and insert it into the table. As before, use the relationship

\[ D = d \times \theta \text{[as]}/200,000 \]

and substitute in \( \theta \) and \( d \) to find the true diameter of this galaxy. Your result is: ____ pc = ____ ly. Does this support our hunch that the glow is indeed a galaxy?

Now see what you found out. There is a galaxy, about the same size as our Milky Way, and in the center of it there is a very bright star-like object, whose light completely overwhelms the light of all the hundred billion stars of a regular galaxy! We now calculate the absolute
brightness of this ‘active galactic nucleus’ (AGN). The distance modulus is found from the distance, $\Delta = 5 \times \log(d)-5 = ____^{mg}$, and you’ll recall $\Delta = m - M$. The apparent magnitude of this object is $m = 13^{mg}$, you find that the absolute magnitude of this AGN is $M = ____^{mg}$.

(A hint: a very far-away object has to be much brighter than $13^{mg}$ to shine at $13^{mg}$ for us. That makes its absolute magnitude a much smaller number than $13^{mg}$, so subtract!). This object, viewed from as far as some of the stars, 10 parsecs, would shine as bright as the Sun!

Such a hugely energetic object, not larger than a few AU’s as we saw, can be nothing else but a many-million-solar-mass black hole, gobbling up a few stars’ worth of mass every year.

In order to support this conclusion, do this calculation for extra credit.

**Calculate the energy output of the quasar:**
The absolute magnitude of the Sun is $M = 4.8^{mg}$. With your value of the quasar’s absolute magnitude, you know that the quasar is _____ $^{mg}$ brighter than the Sun (take the difference). This translates to as many times as bright as $10^{mg/2.5} = ____$ times. The Sun uses up its total mass as fuel in about $10$ billion years, and compared to this the quasar will gobble up _____ solar masses worth of material every year. (The mechanism is that this amount of mass falls into the black hole that the AGN indeed is, and the light we see is coming from the material being scrunched just before it falls in. We have tacitly assumed that the efficiency of energy production in the Sun and in the accretion disk of the AGN are the same, each about 1%).

**Conclusions:**

Is a quasar a large thing? _____________________

How close would you dare to approach a quasar? _____________________
Cepheids are a type of pulsating variable stars, named after the prototype \(\delta\) Cephei in the constellation Cepheus. They expand and contract, become brighter and dimmer with a period in the range of 3 to 100 days. Their brightness changes by a good half a magnitude.

They are large and bright as stars go, with an absolute brightness around \(M_V = -4^{mg}\). That is four thousand times brighter than the Sun! They are visible from great distances. The Hubble Space Telescope can in fact resolve individual Cepheids in several external galaxies.

Henrietta Leavitt in 1908 noticed that they obey a period-luminosity relation. This is not hard to understand: a heavier Cepheid would oscillate more slowly, but it would also be brighter. Such a P-L relation, in turn, can be used to determine the distance of their host galaxies (as long as the galaxy is not too far away, so that we can discern the Cepheid separately): the time period can be measured, and the P-L relation tells the absolute magnitude of the star, then a comparison to its apparent magnitude tells the distance. This is the only way we know how to measure the distance of far-away galaxies. We have other ways to measure galaxies’ distances, but all these other ways rely on a known distance of at least a dozen closeby galaxies. We need the Cepheid method for these closeby galaxies as the \textit{first rung} of the distance ladder. If the Cepheid method has an error, all the rest of the rungs will be in error, and then all our knowledge of the size of the Universe will be wrong. This is why it is so important to get Cepheids’ distances right.

It has turned out to be extremely difficult to set up correctly (i.e. calibrate) the P-L relation though. Early attempts were, no mistake, 250% off. The trouble is that, in order to correctly set up the P-L relation, we need to know the distance to at least a few Cepheids ahead of time. But they are large stars and large stars are very rare. Even the closest one is 900 light years away, far enough that even the Hipparcos satellite’s famously precise parallax measurements could not determine the distance. (The only Cepheid closer than this is the well-known Polaris, but it is an abnormal one, with only a very small change, \(\sim0.05^{mg}\), in brightness.) Something radically new was needed.

A team of astronomers lead by Fritz Benedict (McDonald Observatory, Austin, TX) had the idea to use the fine guidance sensors (FGS) of the Hubble Space Telescope. These sensors were designed to keep the spacecraft properly oriented, but it turned out that they could also be used to determine the motion of bright stars with unheard-of precision. They used the FGS on 10 bright Cepheids, and measured their parallax. They published the results in 2007, out of which we quote here four stars:

<table>
<thead>
<tr>
<th>Star</th>
<th>(\delta) Cephei</th>
<th>(\zeta) Geminorum</th>
<th>(l) Carinae</th>
<th>RT Aurigae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallax</td>
<td>3.66±0.15 mas</td>
<td>2.78±0.18 mas</td>
<td>2.01±0.20 mas</td>
<td>2.40±0.19 mas</td>
</tr>
</tbody>
</table>

The parallaxes are in \textit{mas}, read milli-arc-seconds. They are tiny, meaning that the stars are very far away. (\(1\ \text{mas} = 0.001\ \text{arc sec.}\))

In the first part of this laboratory you will be using a computer simulation of how these four stars look in the sky, and how fast they change their brightness. The simulations are truthful in
that they show the variable stars brighten and dim as they do in fact. (All simulations start at February 15, 2007, 0\textsuperscript{h}00\textsuperscript{m}00\textsuperscript{s} Universal Time.) The simulated sky has the brightness of several comparison stars indicated, so you can estimate the average brightness of each Cepheid. You will ‘observe’ each variable’s period and average brightness, and calibrate the P-L relation yourself.

In the second part of the laboratory you will apply your calibrated period-luminosity relation to determine the distance to two galaxies, NGC5584 and the Andromeda galaxy M31. This same procedure was used in 2011 by a team lead by Adam Riess (Johns Hopkins University) and others to determine the distance to six galaxies, each a host to a Type-Ia supernova. (The picture shows one of these galaxies, NGC 5584, with the bright supernova SN 2007af.) Based on these distances, they could tell the maximum brightness of each exploding supernova, and found, with great precision (±2%) that they all have the (metallicity-corrected) absolute brightness of $M_V=-19.3^{mg}$. They could then use previous observations of 600 other supernovae in various galaxies with well-known redshifts to determine the distance of those galaxies. This gave them a chance to determine the Hubble constant with ±3% precision. As the age of the Universe is the reciprocal of the Hubble constant, this is how well we know now how old and how large the Universe is.

A few concepts and relations, to refresh your memory:

**Parallax:** the yearly orbit of Earth around the Sun is reflected in the stars. They move in tiny circles whose radius (in arc seconds) is called parallax. The reciprocal of the parallax equals the distance to the star, expressed in parsecs, $d[\text{pc}]=\frac{1}{\pi[\text{as}]}$.

**Parsec:** 1 pc = 3.26 light years, a unit of distance.

**Absolute magnitude:** how bright the star would look from a distance of 10 pc. The Sun’s absolute brightness is $M_V=+4.8^{mg}$. The absolute brightness range for stars is approximately from $-12^{mg}$ (largest supergiants) to $+16^{mg}$ (tiniest red dwarfs). The index V refers to visual magnitude (yellow filter).

**Distance modulus:** The difference between apparent and absolute magnitude, $\Delta = m - M$. The farther the star is, the larger the distance modulus; $\Delta = 0$ at 10 pc. The distance modulus is related to the distance of the star as $\Delta = 5 \times \log \left(\frac{d}{10}\right)$; $\log$ means 10-based logarithm. This is equivalent to (for your convenience) $d = 10^{\frac{\Delta}{5}}$. (Units are parsecs for $d$ and magnitudes for $m$, $M$, and $\Delta$.)
PROCEDURE AND LAB REPORT

Date:__/__/20__. Your name: ____________ Partner’s name: ____________ Section: __

1. **Listen to your instructor’s introduction.** You’ll learn a few things that the lecture may not have covered, so pay close attention.

2. **Start up the computer in Windows XP.** If it is running MAC, you will have to restart it while holding down the OPTION key. Use the Student account to log in.

2. **Read the introduction,** then answer these questions:
   (i) Imagine that the P-L relation of Cepheids is incorrectly calibrated and predicts that Cepheids are by 1.6 mg (i.e. four times) brighter than what they really are. How would this affect our knowledge of the distance to external galaxies? __________________________________________

(ii) The longer the period of a Cepheid is the ________ it is.
(iii) Why has it been very difficult to establish the correct calibration of the Cepheid P-L relation? _______________________________

3. **Start up the simulation** (click Desktop→AstroLabs→Cepheids). The ‘WELCOME’ page appears; as you work with the various stars, you’ll always return to this page. Click ‘Introduction’.

   The ‘Introduction’ page shows the constellation of Cepheus as you see it with the naked eye in a dark location in the summer. Identify δ Cephei (the letter is small Greek delta). Start the animation. Observe how it gets brighter and dimmer periodically. Notice that the magnitude is a smaller number when the star is brighter. Go back to the “Welcome” screen.

4. **Click Delta Cephei** and start the animation. Observe how the stars brightens and dims. The graph is called the light curve, brightness (magnitudes) vs. time in days. Note the characteristic light curve of classical Cepheids: they brighten quickly, and return to minimum much slower.

Record the time and brightness of each the maximum and the minimum of the variable. Write ‘max’ or ‘min’ in the first row as appropriate.

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Subtract the time of the first maximum from the second to get a rough estimate of the period. Your result is _____ days. Now, you will get a more precise number if you do the subtraction over five periods, and divide the total time by five. The more accurate result is _____ days.
Record also the average brightness of the star; this will be the average between the maximum and the minimum brightness. Your result is _____ mg.

Insert these values in the table in Part 6 and go back to the “Welcome” screen.

5. Click ζ Gem, l Car, RT Aur and repeat the exercise above, filling in the tables of minima and maxima. (Here, ζ is the Greek letter small zeta. Note the use of the three-letter abbreviations of the constellation names.)

The magnitudes of the stars in minima and maxima will have to be estimated. This is how it is done in real life as well. Pause the animation when the star is in maximum (minimum). Find a comparison star that is just brighter than the variable, and another one that is just dimmer. Subtract and tell how many tenths of magnitude the difference is between the two comparison stars. Based on this, imagine in your mind how much of a difference a tenth of a magnitude would look. Then, tell how many tenths the star is brighter than the dimmer of the two comparison stars (or brighter than the dimmer one). Subtract (or add) to figure out the brightness of the variable star.

You’ll need some practice to do this. In fact, for two hundred years, amateur astronomers all over the world have used this way of estimating the brightness of variable stars and provided great service to professional astronomy.

Use common sense to check that the number you got for the brightness makes sense. Keep in mind that a larger number means a dimmer star!

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</table>

6. Do the necessary calculations in order to determine each star’s absolute magnitude. Use what you learned from the introduction, and fill in the table below. Don’t forget to convert mas to as, recall 1 as = 1000 mas.

The line before the last contains measured values of the extinction of light due to interstellar dust between us and the star, based on the strength of the absorption lines of interstellar matter in the spectrum of the star. You must correct the absolute magnitude for this extinction.
7. **Plot** in the absolute magnitude of each of the four stars vs. its period. The uneven graph paper you use for this is called a *logarithmic* graph paper. The scale on the x-axis is logarithmic, which automatically turns your plot into a plot of $M_V$ vs. $\lg P$, and since Henrietta Lewitt’s discovery we know that this logarithmic plot should put the stars on a straight line.*

Draw the four points in the graph, and mark each with the name of the star.

Using a ruler, draw a straight line across the points, as close to each as possible.

**Extra credit:**
Read off, from your line,

(i) the $P = 10$ days intercept, $a = $ ____ $mg$,

(ii) the slope of the curve, $b$ = $ $ ____ $mg$.

The P-L relation is $M_V = a + b \times ( \lg P - 1 )$.

---

* Lewitt used observations of many Cepheids in the Large Magellanic Cloud (LMC), a satellite galaxy of our Galaxy. These Cepheids are all at the same distance, so she could conclude that the P-L relation was a straight line, but no knowing the distance to the LMC she could not tell where to draw the line in the graph.
Now understand what you have done. You have measured each of the four star’s period, and
determined their absolute magnitude, then you have established a relationship between them.
(We call it Period-Luminosity relation, although in fact it is period-magnitude relationship. But
absolute magnitude and luminosity are essentially the same thing.)

This relationship can now be used for other Cepheid variables, including those in external
galaxies. Their period is relatively easy to measure, and you can use your graph to read off their
absolute magnitudes. Relating this to their observable apparent magnitudes, you can tell the
distance to these galaxies! This we will do with two galaxies now.

8. Use the animation of M31-V1. The Andromeda Galaxy is the #31 object in the Messier
Catalogue, i.e. M31, and this variable is the brightest truly extragalactic Cepheid of all (except
those in the Magellanic Clouds). Notice that, even if a Cepheid is much brighter than an average
star in the galaxy (the average is about $+5^{mg}$, a Cepheid is $-3^{mg}$, absolute), it is still quite hard to
make out an individual Cepheid in the Andromeda Galaxy, even in the Hubble Space Telescope
image you are using.

Determine the period of this Cepheid using the animation, and insert your answer in the table
below. You’ll notice that it is a long-period Cepheid. Why do you think it is so? Explain:

The measurement of the maximum and minimum brightness of the star is more difficult than it
was for galactic Cepheids, due to crowding – the bright background of the large number of
unresolved stars. This is one of the hard observational problems in astronomy. We suggest to
pause the animation where the star is middle brightness (halfway between maximum and
minimum), and use the comparison stars then. Enter your estimate in the table.

<table>
<thead>
<tr>
<th>Star</th>
<th>V1 – M31</th>
<th>V1 - NGC 5584</th>
<th>V2 - NGC 5584</th>
<th>V3 - NGC 5584</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period (P)</td>
<td>days</td>
<td>days</td>
<td>days</td>
<td>days</td>
</tr>
<tr>
<td>Apparent brightness (m)</td>
<td>mg</td>
<td>mg</td>
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<tr>
<td>Absolute brightness (M)</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
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<tr>
<td>Distance modulus ($\Delta$)</td>
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<td>mg</td>
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<tr>
<td>$\Delta$ averaged</td>
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<tr>
<td>Distance (d)</td>
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<tr>
<td>Distance (d)</td>
<td>light years</td>
<td>light years</td>
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Now, you can use your calibrated P-L relation (the plot above) to read off the absolute
magnitude of V1-M31. Put this star on the plot, and indicate its name there. Enter your answer
in the table now, then fill out the rest of the column. Based on your result, you can tell, is M 31
part of our Galaxy (which is $\sim 100,000$ light years across), or is it outside the Galaxy?
9. Use the animation of the Cepheids V1, V2, V3 in NGC 5584. This is one of the closest Type-Ia supernova host galaxies (SN 2007af). Your measurement of the distance to NGC 5584 can be used to calibrate the Type-Ia supernova method of distance determinations. Repeat the exercise as in Part 8. This time, you need to average the three results for the distance modulus. They are supposed to be equal, but the uncertainty in the brightness estimates introduces an error which will be lowered by the averaging. *(Watch out: if the three values for Δ are very different, say they differ by more than a half a magnitude, than you must have made a mistake. That is not a statistical error and it cannot be corrected by averaging. It such a case you must find the error and correct it before proceeding.)*

Is the galaxy NGC 5584 closer or farther than the Andromeda Galaxy? ___________________.

10. Observe the eruption of SN 2007 af in NGC 5584. This was a Type-Ia supernova discovered on March 1, 2007 by Ko-ichi Itagaki. According to your observation, it attained its maximum brightness on ___________. It would be too difficult to tell its maximum brightness from the animation, because of crowding around both the supernova and around possible comparison stars. It was much easier to tell the maximum brightness using a small telescope in which the galaxy does not look bright. The maximum brightness turned out 13.0$^\text{mg}$, observed by many astronomers all around the world. Using this data, what was the absolute magnitude of SN 2007 af at maximum light? _______________. *(Show your calculation in the bottom of this page.)*

This value, and a few other similar determinations of Type-Ia supernova absolute brightnesses, serve to *calibrate* the next rung of the *cosmic distance ladder*. Now, any Type-Ia supernova in any galaxy, with its maximum brightness observed, would allow you to tell that galaxy’s distance.
Lab #25: The Rotation of the Sun

The time of spin of the Sun has been measured by following the motion of various features (“tracers”) on the solar surface. The first and most widely used tracers are sunspots. Though sunspots have been observed since ancient times, it was only when the telescope came into use that they were observed to turn with the Sun and that rotation could be seen at all. Sunspots are temporary phenomena on the “surface” of the Sun (the photosphere) that appear visibly as dark spots compared to surrounding regions. They are caused by intense magnetic activity, which inhibits convection (which normally brings up heat from the depths of the Sun), forming areas of reduced surface temperature. Although they are at temperatures of roughly 3,000-4,500 K, the contrast with the surrounding material at about 5,780 K leaves them clearly visible as dark spots. If a “dark” sunspot were isolated from the surrounding photosphere it would be still brighter than the electric arc. Since sunspots are on the surface of the Sun, which is spherical in shape, they become foreshortened as they move across the face of the Sun. They can be as large as 80,000 km (50,000 miles) in diameter, making the larger ones visible from Earth without the aid of a telescope, although we can look directly into the Sun only a few minutes before Sunset, when the Sun is not overwhelmingly bright.

In this lab, you will trace the movement of sunspots over a sequence of days based on images taken by the SOHO spacecraft (SOlar and Heliospheric Observatory), operated jointly by NASA and the European Space Agency (ESA).

PROCEDURE AND LAB REPORT

Date: ___ / ___ / 20___. Your name: _________ Partner’s name: _________ Section: __

1. **Open the picture file** by double clicking on the setup file *Sunspots.pdf*, located in the Desktop/AstroLabs/AstroDocuments folder. Use the down arrow to see the daily change due to the rotation of the Sun.

2. **Read off longitudes:** For each of the sunspots (A, B, and C), record the date and the longitude for each day in the chart below as they progress across the face of the Sun.

3. **Determine daily motion:** In each table fill in the last column by taking the difference of the longitudes as they change in any one day.

**A note to $4, f, on the next page:**

“Human error” should not be the answer. That would mean that you did your job wrong; that hopefully did not happen.
4. **Interpret your results:**

   a. Do all sunspots “move” around the Sun with the same rate?  
      ________.

   b. What was the average daily rate the sunspots appear to be moving?  
      ________.  
      (Average for all three spots.)

   c. Did some spots seem to change in size or shape?  
      ________
      If so, explain how and why:

   d. From your answers you can conclude that sunspots appear to move around the Sun at  
      the rate of ________ degrees per day. However, this is not the true rotation of the Sun.  
      We are watching the Sun from an Earth that orbits the Sun in 365 days, and that is  
      almost exactly one degree a day. Sunspots in actual fact must be moving 1°/day faster  
      than they appear from Earth. You can conclude that sunspots (and so the Sun itself)  
      rotate at a true rate of ________ degrees per day.

   e. At this rate, how long a time is needed to make one full rotation?  
      ________ days.

   f. Other measurements give an average value of 25.375 days for the rotation of the  
      Sun. Did your procedure give a reasonably close value to this? Calculate the percent  
      difference: ________ %. It is not expected that any two measurements ever give exactly  
      the same answer. There is always a little measurement error; that is part of the  
      process. What do you think the main reason for the difference is?

      ________
Lab #50: The Pleiades

The Seven Sisters, a bright open star cluster, go by the official names of “The Pleiades”, or M45 (which is the #45 object in the famous catalogue of Charles Messier).

The mythology of the Seven Sisters:

Maia, Alcyone, Merope, Electra, Celaeno, Taygeta, Sterope, plus their father and mother, Atlas and Pleione (which makes it 9 stars altogether).

Out of these, Pleione (5.05 mg), Celaeno (5.45 mg), and Sterope (5.76 mg) are so dim that they are quite hard to make out without a telescope. This leaves six stars visible to the naked eye. They form an open star cluster the size of the full Moon inside the constellation of Taurus.

Another version (which does not agree with our present-day names of these stars) says that only six of the seven sisters are normally visible, the seventh fading, because Merope was the only one who consorted with a mortal (Sisyphos), while all the others were pursued by various gods. (Cf. Merope Gaunt of Harry Potter.)

They are named “Pleiades” (Πλειάδες) after their mother “Pleione (Πληιόνη)”.

They were nymphs in the train of Artemis. According to Hesiodes, they were pursued by Orion, and turned into doves to preserve their safety. (Indeed, Orion follows the Pleiades in the sky’s daily motion.)

In Japan, the Pleiades star cluster is called “Subaru”. The Pleiades is the logo of the Subaru car company.

Another open cluster nearby:

The Hyades (Ŷάδες) were also daughters of Atlas, half-sisters of the Pleiades. Their brother Hyas (Ŷάς) was slain by a boar he hunted, and the ever-weeping rain-nymphs Hyades mourn their brother. They have been placed in the sky by Zeus as a symbol of family love. They are rarely mentioned by their individual names.

Indeed, when the Hyades (in the constellation of Taurus) are visible, which is in wintertime, Greece has its rainy season.

The bright star Aldebaran appears to belong to the letter V formation of the Hyades cluster, but in reality it is much closer (65 light years, vs. the 150 light years to the Hyades.)
PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: __________ Partner’s name: __________ Section: __

1) Find the Pleiades in the sky. How many stars can you count with the naked eye? ______

2) What magnitude is the brightness of the whole cluster together, according to your estimate? ____mg.

3) Find the Pleiades using SkyGazer, and fill in the data: The Pleiades star cluster is _______ light years away. It is located in the constellation of ___________ (official name), that is, the _____________ (English name).

4) Aim a telescope at the Pleiades. Use the smallest magnification you can to make sure as much of it fits in the field as possible. One of the star charts is a mirror image, and one is a regular image. Find out which one matches with the image in telescope you are using (it depends on the optical system of your telescope and may be different for different telescopes). You are using chart _____. Identify the named bright stars in the telescope’s field.

5) Find Alcyone and Electra, two stars that are almost exactly east-west from each other.

6) As time passes, these stars will move towards the west, and they slowly drift out of the telescope. Use a timer to find out how long it takes for the second of these two stars to follow the first one. Watch the stars drift out of the field: start a timer when the first one leaves the field, and stop it when the second one leaves. You find that the first one to leave is ______, the second one is ______, and it follows in ______ minutes.

7) The reason why stars drift out is that Earth rotates. Because Earth rotates one full circle, 360°, in one day, it rotates ____° every hour, that is ____° every minute. This means that the two stars are separated by ____° in the sky.

8) An object that subtends a half a degree angle in the sky has a physical size a 100 times smaller than the distance to it. Because these two objects are separated by _____ times a half a degree in the sky, they are separated by a distance ______ times smaller than their distance.

9) Knowing how far the stars of the Pleiades are from us, you’ll find that these two stars are separated by a distance of ______ light years.

10) Because you see many stars in the Pleiades that are much closer to each other than this, you conclude that the closest stars in the Pleiades are separated by much less than _____________.

(11) For extra credit: indicate two reasons why this measurement does not provide a very accurate result for the distance between these two stars. (Nevertheless, the main conclusion is still correct.)

(i) _______________________________________________________________________

(ii) _______________________________________________________________________

(iii) Why did we have to take two stars that are exactly East-West from each other? ____________________________________________________________________

The Pleiades

Chart A:

Chart B:
Lab #51: The Size of the Moon

Sizes of celestial objects as they look in the sky cannot be given in feet or miles or meters, because they look small or large depending on their (usually unknown, and always nontrivial) distances. An airplane “is” large at the airport but small when you see it flying high up in the sky. The apparent sizes are measured as angles.

PROCEDURE AND LAB REPORT

Date: __ / __ / 20__. Your name: __________ Partner’s name: __________ Section: __

1. Look at the Moon through a straw. Does it fit? How many times do you think the Moon would fit in the hole in the straw?

Measure how long the straw is: _____ mm. Measure the diameter of the straw: _____ mm. Then the straw is ____ times longer than it is wide. Any object that is 100 times farther than its size will appear as 1/2 degree in size. You conclude that the hole in the straw appears to be _____ degrees. Because the Moon appears ____ times smaller than the hole in the straw (estimate!), its size is measured to be ______ degrees.

2. Compare the size of the Moon to a penny.

Take a penny and hold it at arm's length. Is it large enough to cover the Moon? __________.

Take one of the sticks with a penny attached to the end. The length of the stick is 180 cm. Try to cover the Moon with the penny, holding the stick in front of your face.

Now measure the diameter of the penny, _____ mm. The penny was held at ______ mm from your eyes, so it was _____ times as far as its size. Then the penny looked _____ degrees in diameter. If it can just cover the Moon, then the Moon is also _____ degrees in size.

* A nearsighted person with too weak glasses usually overestimates the size of the Moon! */
3. Measure the size of the Moon in the telescope.

Aim a telescope at the Moon. Use low magnification (50 × is best) so all of the Moon fits in the field. Observe that the Moon moves due the rotation of Earth.

Use your wristwatch, a timer, or a stopwatch (many cell phones also include one) to measure the time the Moon takes to leave the field. More precisely, measure the time between when the Moon touches the edge of the field and when the center of the Moon’s disk leaves the field. The result was _________ seconds.

You know that the sky turns 360 degrees in 24 hours. How many degrees did it turn during the time you found? __________ degrees.

Note that this is the radius of the Moon. Its diameter is twice as much, _____ degrees.

4. Compare your results in parts 1, 2 and 3. Do they come reasonably close?

____ ___________________________ ___________________________
5. **The distance to the Moon is a known 384,400 km.**
   In the previous parts you found that the Moon was ______ degrees in size. Based on that, what is the size of the Moon? Found: ______________ km.

6. **For extra credit:** If the size of the Moon is what you found above, how large is the crater Copernicus? Find it on the map, and measure its diameter in millimeters on the map. Also measure the diameter of the Moon on the map in millimeters. Find the actual diameter of this crater: ______ km. Would you be able to see an astronaut on the Moon?________.

7. **For extra credit: find a method to measure the size of the Moon more accurately.** Use a reticuled eyepiece. Align the reticule in the N-S direction. Time how long it takes between when the edge of the Moon touches the reticule and when the center point of the terminator touches the reticule.

Then you'll have to draw the shape of the Moon, and calculate how long it would have taken for all of the Moon to leave the field. Turn in your calculations on a separate sheet.
Lab #52a: How to use a telescope? (Refractor)

In this laboratory you will learn how to set up and use the 12-cm (5-inch) refractors. They are small-size as amateur telescopes go. The amateur rage would be 4 to 20 inches in diameter. Most modern astronomical telescopes are reflectors; in those the main optics is a concave mirror located in the bottom of the tube. The ones you will be using in this lab are refractors, which use a lens in the front as main optics. The objective forms image at the back of the telescope (The zenith prism turns the viewing by 90°, which is very convenient when you are looking at a star high up. Zenith is the point straight up – hence the name.)

The image formed by this system is viewed through an eyepiece. The magnification of the telescope is calculated as $M = \frac{f_{objective}}{f_{eyepiece}}$, and you can use various eyepieces of your choice. A good starting point is an $f = 26\ \text{mm}$ eyepiece. What will the magnification be with this eyepiece? What would be the magnification with an $f = 9\ \text{mm}$ eyepiece? Enter your answers in the lab report.

![The schematic of a refractor with a zenith prism](image)

Aiming the telescope at an object needs some care. Due to magnification, the size of the field you see in the eyepiece is little (nothing much larger than the size of the Moon would fit in the telescope), so you need to use an aiming device. For this purpose, a small telescope called the findertelecope is attached, and it always points at the same star. In order to aim at an object in the sky, you’ll need to turn the scope so that the object shows up in the finder first. You’ll need to get your star exactly in the middle of the crosshair, and then the star will show up in the eyepiece. For precise aiming you’ll be using the fine adjustment knobs. (You should not pull the telescope tube for adjustment!)

Once you aim your telescope at a star, you’ll notice that it is moving and it quickly leaves the field. Earth’s rotation causes the sky turn (apparently), and the telescope magnifies this motion. It takes only a minute or two for the star to move out of the field. As the stars “move” on a circle around the axis of Earth (which points at the North Star), once in 24 hours, the telescope has to be turned around this same axis.
The telescopes we are using in this laboratory exercise have a rudimentary mount. It can turn around a vertical axis and a horizontal axis. Such a mount is called an *altazimuthal mount*. You will need to keep tracking the stars manually by turning the telescope around both axes simultaneously.

Once you have a star in the field, you have to *focus* the telescope. (Do not confuse *focusing* with *aiming*. Focusing means moving the eyepiece closer or farther from the main lens, making the image as sharp as possible.) Take off your glasses if you have any, and place your eyes as close to the eyepiece as you can. Grab the focuser knob and turn it this way and that until the star is as small of a dot as you can make it. Every time you look in the telescope you’ll need to focus it, because your eye changes all the time, and other people’s eyes are different from yours.

Notice that you want the stars to be as tiny dots as you can make them. As you move the eyepiece far from focus in either direction, the star looks like a large disk with a black hole in the middle. That is not the star’s image; you need to turn the focuser knob to make the star little again. All stars look like dots in a telescope; their disks are so tiny that even the largest telescopes cannot ever resolve them.

Telescopes are precise and sensitive devices. Handle them as you would handle an eggshell. In particular, never use force for anything: if it does not move easily, you are doing it wrong, and you should ask your instructor for help.

Occasionally some parts of the telescope may become loose, or the finder may not stay parallel to the main scope. If that happens, ask your instructor to tighten the loose parts, or parallelize the finder with the scope. Don’t try to do this yourself.
PROCEDURE AND LAB REPORT

Date:__/__/20__. Your name:_________ Partner’s name:_________ Section:__

1. **Form groups** of two students; **listen** to the introduction by your instructor.

2. **Read the introduction and answer the questions.** Your telescope has a focal length of \( f = ____ \) mm; with a 26 mm eyepiece its magnification would be, \( M = ____ \times \). With a 9-mm eyepiece, \( M = ____ \times \).

3. **Examine the Orion refractor.** It might be difficult to learn how to do this in the dark, so do this **in the well-lit laboratory.**
   -- Insert an \( f = 26 \) mm eyepiece into the telescope, and find the **focuser knob** and turn it.
   -- Push the telescope around both axes to see how it moves. After that, try out both **fine motion** knobs.
   -- Find the findertelecope, and identify the leg adjustment bolts. Make sure they are tight.
   -- Take off the two lens caps and put them in the ‘collection box’ in the laboratory. Lens caps are notoriously easy to lose in the dark when taken outside.

4. **Take the telescope outside.**
   -- Hold the scope by the tripod and don’t try to list it by the telescope tube. Your instructor should demonstrate how to grab it safely. When outside, make sure your telescope is stable enough and does not tip over.
   -- Aim the telescope at any bright star. It should show up int the finder first. Use the two fine motion tubes to center the star in the finder, then look into the larger scope.
   -- Focus the image with the focuser knob. How little did you manage to make the star’s image? Describe it in a few words:________________________________________.

   -- Observing the star you will see that it is moving out of the field. Using your watch, estimate how many minutes (or seconds) it takes for the star to move from the center of the field to the edge. _______ (It is advisable to do this with a star close to the equator; otherwise it will move too slowly.) The name of the star you looked at is:__________________

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<th>Description</th>
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<td><strong>Castor</strong></td>
<td>( \alpha ) Geminorum</td>
<td>The northern one of the two stars of the Twins.</td>
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<tr>
<td><strong>Alcor and Mizar</strong></td>
<td>( \zeta ) Ursae Maioris</td>
<td>The middle star of the handle of the Big Dipper.</td>
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<tr>
<td><strong>Albireo</strong></td>
<td>( \beta ) Cygni</td>
<td>The head of the Swan.</td>
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<td>-</td>
<td>( \gamma ) Andromedae</td>
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</table>
5. **Aim at a double star in the sky.** Your instructor will tell you which one to choose from the four listed ones below. Ask him/her which one is high up tonight.
   -- **Turn the focusing knob**
   this way and that until the star appears to be as tiny a dot as possible.
   -- **Make a drawing of what you see in the field.**
   The circles represent the field of view in the telescope.

6. **Turn the focusing knob** so that the eyepiece moves out of the telescope a few millimeters. Make a drawing of what you see in the field now.

7. **Turn the focusing knob** back and beyond correct focus, so that the eyepiece moves into the telescope a few millimeters. Make a drawing of what you see in the field now.

8. **Which one** of the above situations is a correctly focused telescope? ________

9. **Center your double star and replace the eyepiece** with a 10 mm eyepiece; refocus. The image of the stars will appear blurred and magnified. Do you think what you see is really the disk of the star, yes or no? _____. If no, what do you think is causing the star look like a blurred disk at high magnification? ________________________________.

10. **Take the telescope back inside.** Make sure of the following:
    a. The two lens caps are replaced.
    b. The scope points straight up.
    c. The large (26-mm) eyepiece is in the scope, the 9-mm one on the tray, upside up.
    d. The telescope’s legs are all pulled in short.
    e. The scope is put in a place where it is not blocking the way.
Lab #54: Features of the Moon
PROCEDURE AND LAB REPORT

Date: __/__/20__.  Your name: ___________ Partner’s name: ___________ Section: __

1. Set a telescope on the Moon. Focus the image. Find out the data of your telescope.
   The Moon is ___ days old today.
   The optical design of the telescope: ____________________.
   Telescope diameter: _______________ Objective's focal length: _______________
   The focal length of the eyepiece: ________ Calculate the magnification: _______ x

2. Orientation and terminator.
   Some telescopes give you a regular image, and others give a mirror image. As a baseline, look at the Moon with the naked eye. Which of the two images corresponds to what you are seeing? You may want to turn the map the way the Moon is in the sky. Indicate the “up” direction on the correct map with a red marker. Draw the location of the terminator and blacken out the dark part of the Moon.

3. Find three marea that are visible now in the telescope using the attached Moon map. Indicate their places with numbers 1, 2 and 3 on the picture above. I have found the following maria:
   #1: __________________________,
   #2: __________________________,
   #3: __________________________.
4. Find a large crater visible in the telescope today. Indicate it with #4 on the picture above. Use the laminated Moon map to find its name.
   I have found the following crater: #4:______________________.

5. Find a crater along the terminator. Indicate its approximate position in the above picture with #5, and record its name. Using a high magnification eyepiece, center your crater in the field of the telescope and show it to your instructor. I have found the following crater on the terminator: #5:______ Instructors initials: correct _____, incorrect ________, correct but not along the terminator __________.

6. Using higher magnification, find a crater with a visible central peak and show it to your instructor.
   Found: _____ (instructor's initials).

7. For extra credit: find any of the mountains or valleys on the Moon and show them to the instructor. Look for one close to the terminator. Name: __________________
   Extra credit: ____, ____ (instructor's initials).
Lab #55: The Height of Polaris

The size of Earth was unknown for quite some time and has been “discovered” several times and then lost again. To measure it is an easy experiment to do: all it requires is some understanding of the geometry of the sphere.

A similar experiment was performed more than 2,000 years ago (in 240 B.C.) by the Greek astronomer Erathosthenes, working in the Egyptian city of Alexandria. His astronomical measurement came within 2% precision of the modern value, and his main limitation was that in antiquity no precise way existed to measure the distance between two cities, which he needed for comparison.

The astrolabe is an ancient device invented in 150 B.C. by the greatest Greek astronomer Hipparchos on the Island of Rhodes (he is also the founder of trigonometry). It can be used to measure the altitude (height) of stars over the horizon. The picture below is an astrolabe quadrant, dated 1388, now in the British Museum. On the next page you’ll find a picture of the simple device you are going to make yourself.

A good way to determine your geographical location is based on the Pole Star in the Little Dipper, Polaris. It is special in that, during the night as Earth spins around, the sky seems to turn around the poles, but Polaris stays in the same location. Once you learn in this lab where it is in the sky, you will always find it in the same place.

We have asked another class of astronomy in Guatemala to take the same measurement as you will be doing. They said they saw Polaris quite low over the horizon, and their result of the measurement of the height of Polaris was 15°. You may want to know that Guatemala is straight down south of Oxford by 1300 miles. The more South you go, the lower Polaris will be over the horizon.
PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: ___________ Partner’s name: ___________ Section: __

1. First you need to make your own astrolabe.
   Follow the pictures below. A few pointers come in handy:
   The twine will hang down vertically and let you read off the altitude angle of the star you are watching. You will only read the correct angle if the twine pivots around the hole in the protractor, so make sure the knot you tie does not get in the way. (See the “bad” picture.) The straw must be as long as the side of the protractor, and surely it must be straight, otherwise you cannot look through it. Use scissors to cut it to size.
   You want to make sure the string holds the straw secure and it does not come off. Do not use tape, because tape sticks to the protractor and cannot be removed without trace! Use care when making your astrolabe; you’ll be awarded credit on proper accuracy.

2. Learn how to use the astrolabe. For this purpose, aim the straw at a star close to zenith (almost straight up). Look though the straw to see the star. Have your partner read the angle. The angle you find is the distance of the star from zenith, and it should be a small angle like 5° to 15° or something similar. If the reading is not like this, you are reading the wrong scale; you might have to turn the astrolabe around. After this, repeat the exercise with a star low over the horizon; your reading should be an angle just less than 90°. Record your readings:
   Star high up: ____°; star low over the horizon: ____°.

3. Swap with your partner and repeat these measurements. Your partner’s readings:
   Star high up: ____°; star low over the horizon: ____°.
   (They do not have to be the same; the two of you may even look at different stars.)
4. **Find Polaris in the sky.** Ask for your instructor’s help if needed.

5. **Aim the straw at Polaris.** Look though the hole in the straw and make sure Polaris is visible through the hole and that the twine is hanging down next to the protractor. Have your partner read off the angle the scale says behind the twine. Use a flashlight if necessary. Record your reading for the zenith distance of Polaris: ___°. Now swap with your partner and measure again; the reading is: ___°.

6. **Interpret your results.** As you made two measurements of the same value, you’ll have to average them. (If you are sure one of the two is incorrect, use only the correct one.) You find that the zenith distance of Polaris is ___°.

   As zenith is obviously always 90° up, the altitude of Polaris will equal 90° minus its zenith distance, which you calculate as ___°. This number is your result for the height of Polaris.

7. **Calculate the size of Earth.** The difference in the height of Polaris as seen from Oxford and from Guatemala is Δ=___°. Measure the Oxford-Guatemala distance on the map you’ll find on the wall of the laboratory; your result is \(d=\)_____ miles. If Δ degrees are \(d\) miles, calculate how many miles will be 360 degrees. Your result is _____ miles, and this is your result for the circumference of the Earth.

8. **The diameter of the Earth** will be found if you divide the circumference by \(\pi=3.14\). Your result is: _____ miles.

9. **How well does your result compare with the correct value for the diameter of the Earth,** which is 8,000 miles? Did you do better than Erathosthenes 2250 years ago? ____________

10. **Have your instructor inspect your astrolabe and record the grade for how carefully it was made.** Instructor’s initials and mark: ______.

11. **Take apart your astrolabe,** put the parts in the boxes, and turn in your report.
Lab #57: Saturn’s Ring and the Roche Limit

The ring of Saturn was formed by the breakup of a small moon that drifted too close to the planet. It was pulled apart by the tidal forces of Saturn when it came within the Roche limit. This limit, named for the French mathematician Éduard Roche, would be the distance where the tidal force due to Saturn is larger than the gravity of the moon. Any piece of rock on its surface would be pulled off, and eventually the whole moon would end up torn to pieces.

You will need to understand that the only force of any importance is gravity. The strength of the rock will not matter; it is not strong enough to keep pieces of material from escaping when the total of the gravity is pulling them up into the sky.

You might realize that the strength of the rock is too weak to keep a moon together when you think of the fact that any moon larger than about 500 miles is a round shape. The round shape is formed, surely, by gravity, while the strength of the rock wants to keep it an irregular shape. Gravity wins.

PROCEDURE AND LAB REPORT

Date: __/__/20__. Your name: ___________ Partner’s name: ___________ Section: __

1. Measure the diameter of the ring, as observed in a telescope. You’ll need an eyepiece in which the edge of the field looks sharp for the observer. (You may have to keep your glasses on to achieve this.) Aim at Saturn, and switch off the clock drive (if any). Saturn will drift out of the field. Use a stopwatch to measure the time it takes for Saturn’s ring to drift out of the field, from position A to position B. Record your result, then swap with your partner and have him/her measure the same thing again. The two times are: _______ and _______. If the two aren’t close, try again. When satisfied, take the average: _______.

![Diagram of Saturn's ring with positions A and B marked]
2. **Measure the diameter of the planet**, as observed in a telescope.

Aim again at Saturn, and keep the clock drive switched off (if any). Saturn will again drift out of the field. Measure now the time it takes for Saturn’s disk to drift out of the field, from position C to position D. Record your result, then swap with your partner and have him/her measure the same thing again. The two times are: _______ and _______. If the two aren’t close, try again. When satisfied, take the average: _______.

![Diagram of Saturn with positions C and D marked](image)

3. **How many times is the ring larger than the planet?** Divide: _______ times. Saturn’s radius is 55,000 km, so calculate the radius of the ring: _______ km.

![Image of asteroid Kleopatra shaped like a dogbone](image)

Moons and asteroids often look very similar on pictures; many moons are in fact captured asteroids. The picture above shows asteroid Kleopatra\(^1\) – shaped like a dogbone. In the following, we assume that an icy object, shaped like Kleopatra, got as close to Saturn as the rings. We will assume, for simplicity, that this one-time “moon” of Saturn’s consisted of two spherical icebergs, A and B, each 1 km in size, just touching in the middle. We’ll calculate how much force of gravity is holding them together, and how much tidal force is ripping them apart.

\(^{1}\) Credit: S. Ostro et al (JPL), Arecibo Radio Telescope, NSF, NASA.
We’ll use Newton’s law for the force of gravity, \( F = G \frac{m_1 m_2}{d^2} \), between objects of mass \( m_1 \) and \( m_2 \), separated by a distance \( d \) between their centers: \( G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2 \). Saturn’s mass is \( 5.7 \times 10^{26} \text{ kg} \), and the icebergs would be \( 5.2 \times 10^{11} \text{ kg} \) each. (The units have already been converted, for your convenience, so that you’ll never have to do any conversion yourself.) The letter \( N \) stands for the unit of force, Newton, equal about \( \frac{1}{16} \) pounds.

4. **Calculate the force of gravity** between pieces A and B. Their centers are, obviously, \( 1 \text{ km} \) apart. Fill in the calculation,

\[
F_{A-B} = G \frac{m_1 m_2}{d^2} = \left( \frac{m_1}{(d)} \right) \left( \frac{m_2}{(d)^2} \right) = N.
\]

5. **Calculate the force of gravity** between Saturn and the piece A. Their centers are, obviously, as far apart as the radius of the ring. Fill in the calculation,

\[
F_{S-A} = G \frac{m_1 m_2}{d^2} = \left( \frac{m_1}{(d)} \right) \left( \frac{m_2}{(d)^2} \right) = N.
\]

Be very careful to keep at least 7 valid digits in the answer, you’ll need them!

6. **Calculate the force of gravity** between Saturn and the piece B. Their centers are, obviously, as far apart as the radius of the ring plus one kilometer. Fill in the calculation,

\[
F_{S-B} = G \frac{m_1 m_2}{d^2} = \left( \frac{m_1}{(d)} \right) \left( \frac{m_2}{(d)^2} \right) = N.
\]

Be very careful to keep at least 7 valid digits in the answer, you’ll need them!

7. **Calculate the tidal force** ripping apart pieces A and B. Saturn attracts both, but it will attract A stronger than B as A is closer to Saturn than B is. Only the difference between the two forces is ripping them apart,

\[
F_{\text{rip}} = F_\text{A} - F_\text{B} = N \quad \text{(Fill in the blank indices and the result.)}
\]

8. **Which one is stronger**, the force ripping apart pieces A and B, or the force of gravity keeping the ‘moon’ together? Your answer should be that the ripping force is larger, but how many times? \______________\. (If your answer did not come out right, ask your lab instructor to help you chase down the mistake in your calculation.)

9. **Now imagine a “moon” of Saturn is** not dogbone-shaped like Kleopatra is. Will it still be ripped apart when it comes as close to Saturn as the ring is? (The borderline distance for a moon to be ripped apart by tides is called the Roche-radius.) Describe what you think:

\______________

\______________

\______________
Acknowledgements and copyright notices:

Lab 3a,b, Sizes in the Solar System, and A scale model of the Solar System, are courtesy of Drs. Donald J. Summers and Eric M. Aitala, University of Mississippi.

Voyager SkyGazer is a planetarium program by Carina Software & Instruments, Inc.

TheSky6 is a planetarium program by Software Bisque, Inc.

Lab 11: The mass of Jupiter: The laboratory uses software from Project CLEA, sponsored by Gettysburg College and the National Science Foundation.


Lab 18, Cepheid variables and distances: This is an unauthorized copy of Jay M. Pasachoff and Ronald W. Goebel, (Williams College): Sky and Telescope, March 1979, pp. 241-244. Not for public circulation.

Lab 25, The rotation of the Sun: the images used were taken by SOHO, operated jointly by NASA and the European Space Agency (ESA).

Lab 55, The height of Polaris: The picture of and astrolabe quadrant dated 1388, at the British Museum. Image licensed under the terms of the GNU Free Documentation License.

Lab 57, Saturn’s ring and the Roche limit: Credit for the image of the asteroid Kleopatra: S. Ostro et al (JPL), Arecibo Radio Telescope, NSF, NASA.

Special thanks are due to Iva Cramer for a careful editing of most of this manual.

The laboratory web page is at

www.phy.olemiss.edu/Astro/Lab/Lab.html.

Check your grade every week on this page!

Front page picture: SN1994d supernova in NGC 4526

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