For use in Astronomy 104 only.
(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!
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Lab I: 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 21st 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 21st century, but it is still used for educational purposes.

As a classical refractor, it has a very long focal length \((f = 180 \text{ inches})\). 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 \(1/3 \text{ arc second}\); 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: __________________________ Section: __

1. Read the review, and listen to your instructor’s introduction. If available, watch the video.

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 reflector, 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 refctor, 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 IIa: Draw planets preparation

Observations of planets are done for our classes with the telescope best adapted to high-resolution viewing, which means we use the large 15-inch refractor in Kennon Observatory. The activity involves careful viewing and drawing of Jupiter, Saturn, Venus and Mars – whichever are available during lab time.

The whole point in these observations is to discern all the small detail that can be seen with the given resolution of the telescope. This means careful focusing the scope, and careful watching of the field of view several times, spending a long time (a couple of minutes at least) at the eyepiece. Making a drawing, then looking again to correct the drawing, and repeating this cycle several times is the best way to train your eye and brain to discern the small details that are on the borderline of visibility.

This is a learning process. As there is only a short time for each student to spend in the dome, we now offer a way to prepare, comfortably in front of a computer, to simulate the viewing and drawing procedure. You’ll need to do this lab ahead of the observation session, as directed by your instructor.

For this exercise, you need a pencil (pen will not do), and access to a computer that has at least 1200 pixel resolution (which is not hard these days). The necessary simulated images are posted on the web, accessible from the laboratory website at www.phy.olemiss.edu/Astro/Lab/Lab.html, clicking on the ‘Materials’ link. The images are under ‘Draw a planet preparation’.

Each image comes in two versions. The version called ‘150 x magnification’ simulates more accurately your first impression of the view in the telescope. It also tells you the size and proportions of the drawing you have to make for the practice. Your first job will be to make a drawing of this view.

Upon more careful observation you will notice that the ‘150-times’ picture does not let you see all the details on the picture; prolonged viewing in the telescope reveals more detail on the face of the planet. This is simulated on the ‘600 x magnification’ picture. (To see it on your browser, hit the ‘back’ button, then the ‘600 x’ link.) This picture shows about as much detail as you can see in the telescope after long viewing and a strong effort at discerning all detail. You’ll need to make another drawing, with the same proportions as the ‘150 x’ drawing, but the details filled in with what you see on the ‘600 x’ image. To illustrate how a well-done pair of such drawing looks like, here is a similar one at the bottom of the next page.

Note that the planets spin and their cloud features change over time, so that the details you actually see in the telescope will not be the same as in these drawings!

Your drawings need not (and should not!) be artistic. The should be realistic, have the details that are in fact visible in the field of the telescope. Please pay particular attention to the proportions of the sizes, e.g. the size of the planet and the location of the Moons as compared to the size of the whole field of view.
PROCEDURE AND LAB REPORT

Date: ___/ __ / 20__.  Your name: __________________________  Section: ___

1. **Read the introduction**, find and review the pictures on the web.

2. **Answer this question:** How long and how many times do you think you’ll have to watch a planet in the telescope (when it comes to a real observation) in order to see all the small features on its surface? ____________________________.

3. **View the first picture** at 150 x magnification and make a drawing of the field in the circle on the left.

4. **In the circle on the right, draw a copy** of the ‘150 x’ drawing but leave the face of the planet blank.

5. **View the picture** at 600 x magnification and fill in the blank face of the planet in your drawing on the right.

6. **Repeat this exercise** with the remaining three sets of pictures.

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*Here is a reasonably good drawing to indicate how it should be done:*
EXTRA WORK AREA:

Picture One
What planet?

Picture Two
What planet?

Picture Three
What planet?

Picture Four
What planet?
Lab IIb: Draw Jupiter

Jupiter is the largest planet in the Solar System. Careful observation with an astronomical telescope should reveal at least the following features: (i) Next to the planet there are a few moons, appearing as stars, (ii) The planet’s disk is “squeezed”, an elliptic shape due to its fast rotation, (iii) Bands of clouds cross the face of the planet, (iv) A few dark or bright spots may be visible if seeing is good.

Observing a planet is as much an art as science. It takes much practice to really see all that is visible in the telescope. The key is (i) practice and many repeated trials, (ii) care and attention to small detail. You want to focus the image very carefully, position your eyes in the right place on the eyepiece. Remove your glasses if you have any, and place your eye as close to the eyepiece as you can. Find a comfortable position and do not have anything in your hands while observing. It normally takes three-four rounds of looking, focusing, and correcting the drawing to really notice the small details and have them right on the drawing.

The drawings do not need to be artistic, but they need to be precise. Pay special attention to drawing everything there is on the planet, having the proportions of the features correct on the drawing, and having the orientation of the features correct. Use a sharp pencil: it is impossible to do a proper drawing with a blunt pencil or with a pen.

In order to show what may go wrong and what is expected of you. Look at these drawings:

Notice the position of the moons and the spots on the planet change within a few hours, so do not duplicate the above “good” drawing. Now, in the space below, draw the planet and its moons. Another circle is provided in case the first one gets messed up. Note the time (CST is Central Standard Time and CDT is Central Daylight Savings Time). Note the data of the telescope (you’ll find them on a sign affixed to the telescope and on the eyepiece). The magnification of the telescope is calculated as $M = \frac{f_{\text{objective}}}{f_{\text{eyepiece}}}$. 
LAB REPORT: ASTRONOMY 103/104 – Draw Jupiter

Your name: __________________________  Section: ____  Date: __/__/ 200__

Time: _:_ PM C_T  Telescope diameter D = __ in
Objective f = _____ mm  Eyepiece: f = _____ mm

Magnification: ____ ×  Telescope make: __________________

Indicate the name of each moon you saw in the telescope. Put only numbers on your drawing, and find out the names using Sky and Telescope’s Jupiter Profiler available through the website skyandtelescope.org/observing/jupiters-moons-javascript-utility/#; to start the utility click at the bottom of that page where it says “Launch S&T’s Jupiter’s Moons interactive observing tool”; or, alternatively, set SkyGazer at the present date, find and lock on Jupiter, and magnify the view. This part can be done after you come down from the dome.

1: __________________________

2: __________________________

3: __________________________

4: __________________________

(Fill out as many lines as many moons you found.)
Lab IIc: Draw Saturn

Saturn is the second largest planet in the Solar System, and its ring makes it a fascinating object to view in the telescope. Careful observation with an astronomical telescope should reveal at least the following features: (i) The ring, and a dark division in it (the Cassini division). (ii) Next to the planet there are a few moons, appearing as $9-10^{mg}$ stars, one of them brighter (Titan), (iii) The planet’s disk is elliptic shape due to its fast rotation, (iii) Bands of clouds cross the face of the planet.

Observing a planet is as much an art as science. It takes much practice to really see all that is visible in the telescope. The key is (i) practice and many repeated trials, (ii) care and attention to small detail. You want to focus the image very carefully, position your eyes in the right place on the eyepiece. Remove your glasses if you have any, and place your eye as close to the eyepiece as you can. Find a comfortable position and do not have anything in your hands while observing. It normally takes three-four rounds of looking, focusing, and correcting the drawing to really notice the small details and have them right on the drawing.

The drawings do not need to be artistic, but they need to be precise. Pay special attention to drawing everything there is on the planet, having the proportions of the features correct on the drawing, and having the orientation of the features correct. Use a sharp pencil: it is impossible to do a proper drawing with a blunt pencil or with a pen.

Now, as help, we provided a few samples, all of which are incorrect except for one. Once you have chosen the one you see in the telescope, you will draw the planet and its moons in the circle below as you see it. Notice that your drawing will provide more detail and/or will be more accurate than the samples. Another circle is provided in case the first one gets messed up. Note the time (CST is Central Standard Time and CDT is Central Daylight Savings Time). Note the data of the telescope (you’ll find them on a sign affixed to the telescope and on the eyepiece). The magnification of the telescope is calculated as $M = \frac{f_{objective}}{f_{eyepiece}}$. After you are finished with the drawing, identify the moons you saw in the telescope using SkyGazer. Remember that a telescope with a star diagonal will show a mirror image; also, you will need to turn your drawing to match the “up” and “down” directions with those on the computer screen.
LAB REPORT: ASTRONOMY 103/104 – Draw Saturn

Your name: __________________________  Section: ____  Date: __/__/ 200__

Time: __:__ PM C_T  Telescope diameter D = __ in
Objective f = _____ mm  Eyepiece: f = _____ mm
Magnification: ____ ×  Telescope make:

The picture best resembling the view in the telescope is: ______

Now indicate the names of the moons you saw in the telescope. Put numbers next to the “stars” on your drawing, and find out their names from SkyGazer:

1: _____________________________
2: _____________________________
3: _____________________________
4: _____________________________
5: _____________________________

(Fill out as many lines as many moons you found.)
Lab IIId: Draw Mars

Mars, bright as it gets in the sky during oppositions, is actually a very difficult object to observe. It is a small planet. In addition, it receives light from behind our backs, which results in very suppressed contrasts, the same way as it happens to the full Moon.

Careful observation with an astronomical telescope should reveal at least the following features: (i) The planet is a disk, not only a dot, (ii) At least one bright polar cap, (iii) Except right at the time of the opposition, the planet shows some phases, appearing as a not quite full ‘moon’ shape, (iii) In favorable conditions some dark or bright spots appear on the surface.

Observing a planet is as much an art as science. It takes much practice to really see all that is visible in the telescope. The key is (i) practice and many repeated trials, (ii) care and attention to small detail. You want to focus the image very carefully, position your eyes in the right place on the eyepiece. Remove your glasses if you have any, and place your eye as close to the eyepiece as you can. Find a comfortable position and do not have anything in your hands while observing. It normally takes three-four rounds of looking, focusing, and correcting the drawing to really notice the small details and have them right on the drawing.

The drawings do not need to be artistic, but they need to be precise. Pay special attention to drawing everything there is on the planet, having the proportions of the features correct on the drawing, and having the orientation of the features correct. Use a sharp pencil: it is impossible to do a proper drawing with a blunt pencil or with a pen.

You will draw the planet in the circle below as you see it. Another circle is provided in case the first one gets messed up. Note the time (CST is Central Standard Time and CDT is Central Daylight Savings Time). Note the data of the telescope (you’ll find them on a sign affixed to the telescope and on the eyepiece). The magnification of the telescope is calculated as \( M = \frac{f_{\text{objective}}}{f_{\text{eyepiece}}} \). After you are finished with the drawing, identify the features you saw on Mars, using a Web program that gives you a map of Mars viewed from your current direction. Remember that a telescope with a star diagonal will show a mirror image; also, you will need to turn your drawing to match the “up” and “down” directions with those on the computer screen.
Now indicate the names of the features you saw in the telescope. Put only numbers on your drawing, and find out the names using Sky and Telescope’s Mars Profile, available through skyandtelescope.org/observing/interactive-sky-watching-tools/mars-which-side-is-visible/#; to start the utility is at the bottom of that page and is named “Launch our Mars Profiler”. Include the polar ice caps (if you see any).

This part can be done after you come down from the dome.

1: _____________________________

2: _____________________________

3: _____________________________

4: _____________________________

5: _____________________________

(Fill out as many lines as many features you found.)
Lab III: 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: ______________________________ 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. 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.
Parts 3-4 are optional, depending on how much time you have for the observation. Ask your instructor:

4. **Measure the size of the Moon in the telescope.**

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

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

...
Lab IV: Features of the Moon
PROCEDURE AND LAB REPORT

Date: ___/___/20___. Your 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 mareas 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 mareas:
   #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 V: 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 Eratosthenes, 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: ___________________________  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 π=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 Eratosthenes 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 # VII: Spherical Astronomy

The way stars move in the sky is actually quite easy to understand. All they do is they make one circle in 23h56m, around the North (and South) poles. This is called sidereal motion - one circle (360°) every 24h, 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: ________________________________ 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 is just a little up from the equator. 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 #VIII: Orientation with SkyGazer (May-Oct)

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, viewed 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 you will learn, on the way, about the names, the brightness and color of stars, and how to find 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. This lab needs two settings files, Orientation.vgr and EquatorialGrid.vgr, which may be downloaded from the web at www.phy.olemiss.edu/Astro/Lab/Lab.html.

The computers in the lab are all Macintosh, and those only familiar with Windows machines should be prepared for minor differences. The first point of difference you will see is that on a Mac the SkyGazer application does not quit if you close its window. If you find your computer in that state, double-clicking 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: ____________________________ 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, switch off Auto, 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 shape of the Big Dipper and the Little Dipper. In which one of these is Polaris? ________________

5. **Switch on** the constellation figures (click on ). 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 Milky Way is not far from South. (This will happen at different hours in the night depending on the season.)

Find Sagittarius, Scorpius, and the Eagle (Aquila). Find the names of the two brightest stars in Aquila and in the brightest in Scorpius, and read off their data:

\[ \alpha \text{ Aquilae is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}; \]

\[ \beta \text{ Aquilae is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}; \]

\[ \alpha \text{ Scorpii is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}; \]

the brightest of these is ________ with ___ magnitudes; its magnitude is the ___est number.

6. **Look higher up** towards Zenith, and find the constellations of the Lyre (Lyra) and the Swan (Cygnus). Find the two brightest stars of the Swan and the brightest of Cygnus. (Vega, Deneb and Altair form the Summer Triangle.)

Find these stars and read off their data:

\[ \alpha \text{ Cygni is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}; \]

\[ \beta \text{ Cygni is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}; \]

\[ \alpha \text{ Lyrae is named } \underline{\quad}, \text{ ___ light years away, ___ magnitudes; spectral type } \underline{\quad}, \text{ color } \underline{\quad}. \]

Now switch on the constellation boundaries.

Pluto is presently in the constellation of ____________.

7. **Now switch off** the constellation figures, and switch on the Milky Way (click on ). 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 $118^\circ \times 74.6^\circ$ 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 $\square$. 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 (-26.3$^{mg}$, 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 your instructor assigns to you: _____** *(This one should be observable sometime today, but not necessarily at this hour.)* Click View→Center Planet→(Your planet); do not use the Sky Atlas mode. Lock 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$^\circ$ over the horizon (i.e. its altitude on the data panel must be at least 25$^\circ$). You find that your planet is observable only from ____ to ____. (Give the hours; use common sense use common sense in judging when the planet is actually observable!) Drag the clock farther 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 ($\alpha$) and Declination ($\delta$) 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. With 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=50º declination); the radial lines are like geographical longitude lines, except that the readings on them are in hours (e.g. α =10h right ascension). Use the coordinate grid to locate the star at right ascension α =5h17m, declination δ =46º00’. Click on it; what is the star’s name? __________. Now turn the clock an hour or two forward. 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 α =_____, declination δ =_____.

Next find the objects:

1. at α =3h47m, δ = 24º07’ :______________, in the constellation of _______________.
2. at α =6h45m, δ = -16º43’ :______________, in the constellation of _______________.

15. Quit SkyGazer by clicking ⌘-Q, and then restart your computer.
Lab #IX: Gravity

Gravity causes the speed of falling objects to increase. When you drop a ball, it starts off at rest, and it takes some time to pick up downwards speed. The force of gravity on an object (which is the same thing as its weight) is proportional to its mass; but the inertia of an object, which resists acceleration, is also proportional to its mass: these two cancel each other. For this reason (neglecting air resistance) all objects accelerate at the same rate. In this lab you will measure the acceleration due to gravity using a tennis ball, a stopwatch, a tape measure.

There are calculations involved in going from measured time and distance to speed, acceleration, mass, and density, so a simple scientific calculator is needed.

The point in doing this to see for yourself how a simple measurement that you can do yourself results in that you figure out (at least in part) what the inside of the Earth is made of.

You will also see a simple example how scientists use measurements to get those numbers (at this time, the gravitational acceleration) that you find in textbooks as ‘given’.

PROCEDURE AND LAB REPORT

Date: ___/ ___/ 20__.  Your name: ____________________________  Section: __

1. Find a place where you can drop a tennis ball by at least 500 cm. Measure the drop distance. (Just FYI, 500 cm is about 16 feet.) Record the distance here ______ cm.

2. Now drop the tennis ball three times. Measure and record the times in seconds. (Note that it is difficult to actually drop the ball – you can’t lean out of a safe place without danger to yourself. But you can throw the ball horizontally, straight ahead but not up or down: you’ll find the same falling time.)

3. Average the three times, \( (t_1 + t_2 + t_3)/3 = \) ______ sec. (Taking multiple measurements and averaging reduces the error which is always present in all measurements.)

4. Now divide the distance the ball fell by the average time. This is the average speed of the ball during its fall. You get ______ cm/sec.

5. What was the initial speed of the ball just before you dropped it? ______ cm/sec.
6. Now find the speed at which the ball strikes the ground. Is this speed higher or lower than the average speed? ________

7. Averaging the initial and final speeds gives the average speed, equal to
   \[ \text{average speed} = \frac{\text{initial speed} + \text{final speed}}{2} \]. But initial speed equals zero. What factor do you multiply the average speed by to get the final speed? ________

8. What is the final speed then? ________ cm/sec.

9. Divide the final speed by the fall time to get the acceleration due to gravity. Your result is
   \[ g_{\text{meas}} = \text{________ cm/sec}^2 \].

10. How close is this to the textbook value of \( g = 9.81 \text{ cm/sec}^2 \)? Explain in words (and, preferably, tell the percent error). Note that you will not find your measured \( g \) equal to the book value exactly: all measurements have their errors. __________________________

11. Knowing that the radius of the Earth is \( r = 6.37 \times 10^8 \text{ cm} \), find the volume of the Earth. The volume of a sphere equals \( V = \frac{4}{3}\pi r^3 = \text{______________ cm}^3 \).

12. Now use the acceleration due to gravity and Newton’s Law of Universal Gravitation, which says that the force of gravity, which is the same as the weight of the ball, equals \( F = G \frac{M m}{r^2} \), while Newton’s II law has \( F = mg \). Here \( G \) is the gravitational constant \( G = 6.67 \times 10^{-8} \text{ cm/(gr sec)}^2 \), \( M \) is the mass of the Earth; \( m \) is the mass of the ball.
   Solving this equation for \( M \) you get \( M = \frac{rg}{G} = \text{________ gr} \). [Here we denote grams by \( gr \) in order to avoid confusion with the acceleration \( g \).]

13. Divide the mass \( M \) of the Earth by its volume \( V \) to get its density: ________ gr/cm³.

14. The densities of water, rock, and iron are 1.0 gr/cm³, 2.5 gr/cm³, and 8.0 gr/cm³, respectively. What is Earth primarily composed of? __________________
Lab #X: 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 $1 \text{ km} = 1000 \text{ m}$ and $1 \text{ AU}$ 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: ______________________  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 x</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!

If you do not have enough time to do all of this, drop Europa, Ganymede, and Callisto, and drop the JD calculation. For Io, you can directly calculate the revolution time in hours and convert to days.

<table>
<thead>
<tr>
<th>1st elong.</th>
<th>2nd elong.</th>
<th>Elongation distance (a)</th>
<th>Revolution time (T)</th>
</tr>
</thead>
<tbody>
<tr>
<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>
</tr>
<tr>
<td>Europa</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
</tr>
<tr>
<td>Ganymede</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
</tr>
<tr>
<td>Callisto</td>
<td>/ / h m</td>
<td>/ / h m</td>
<td></td>
</tr>
<tr>
<td>Moon</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>( \text{Io} )</td>
<td>( \times 10^{-9} )</td>
<td>( \times 10^5 )</td>
<td>( \times 10^{-4} )</td>
</tr>
<tr>
<td>( \text{Europa} )</td>
<td>( \times 10^{-9} )</td>
<td>( \times 10^5 )</td>
<td>( \times 10^{-4} )</td>
</tr>
<tr>
<td>( \text{Ganymede} )</td>
<td>( \times 10^{-9} )</td>
<td>( \times 10^5 )</td>
<td>( \times 10^{-4} )</td>
</tr>
<tr>
<td>( \text{Callisto} )</td>
<td>( \times 10^{-9} )</td>
<td>( \times 10^5 )</td>
<td>( \times 10^{-4} )</td>
</tr>
<tr>
<td>( \text{Moon} )</td>
<td>( \times 10^{-9} )</td>
<td>( \times 10^5 )</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: \( M_{\text{Jup}} = \) \( \text{________} \) \( M_{\text{Solar}} = \) \( \text{________} \) \( g \). The same calculation, for comparison, tells the mass of Earth: \( M_{\text{Earth}} = \) \( \text{________} \) \( M_{\text{Solar}} = \) \( \text{________} \) \( g \).

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, \( V = \frac{4}{3} \pi R^3 \), to calculate the volume of both planets. (Make sure you have converted \( R \) to centimeters!) Show your results: \( V_{\text{Earth}} = \) \( \text{______} \) \( \text{cm}^3 \); \( V_{\text{Jup}} = \) \( \text{______} \) \( \text{cm}^3 \). Then, calculate the density of both planets, \( \rho = M / V \). (Make sure you have converted \( M \) to grams!) Show your results: \( \rho_{\text{Earth}} = \) \( \text{______} \) \( \text{g/cm}^3 \); \( \rho_{\text{Jup}} = \) \( \text{______} \) \( \text{g/cm}^3 \).

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:

\[ \text{__________  __________  __________  __________} \]
Lab #XII: Introduction to Spectroscopy

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 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**:

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

This tells the wavelength associated with an electron jumping from the $N^{th}$ to the $n^{th}$ orbit (or backwards). The “Balmer series” spectral lines, which we will measure, called Hα, Hβ, Hγ, 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$^{-9}$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

A diffraction grating breaks up mixed colors into constituents

Light in - white

Grating

Light out - spectrum
PROCEDURE AND LAB REPORT

Date: ___/ ___ / 20__. Your name: __________________________ Section: ___

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

(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 bright hydrogen lines (these will be, from red to blue, Hα, Hβ, and Hγ) 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 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. 

**Exercise 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.

**Exercise 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**.

---

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

*(Please ignore 6 and 7, these are for extra credit only.)*

<table>
<thead>
<tr>
<th>Spectrum #</th>
<th>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>
<tbody>
<tr>
<td>#1</td>
<td><strong>Hydrogen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#2</td>
<td>Known gas:</td>
<td>Number of tube:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>Known gas:</td>
<td>Number of tube:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#4</td>
<td>Known gas:</td>
<td>Number of tube:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>Unknown gas:</td>
<td>Number of tube:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#6</td>
<td>Unknown gas:</td>
<td>Number of tube:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#7</td>
<td>Fluorescent light</td>
<td>Gas(es) it contains:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Questions answered:

Set ____
1.: __________________________________________________________________
2.: __________________________________________________________________
3.: __________________________________________________________________

Set ____
4.: __________________________________________________________________
5.: __________________________________________________________________
6.: __________________________________________________________________

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>
</tbody>
</table>
Lab XIII: 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: ________________________________ 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></td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td>The Sun</td>
<td></td>
<td>-</td>
<td></td>
<td>= ly</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 $m = 0.35 \, mg$, so it is a very bright, bright, faint, very faint star.
   - Its absolute magnitude is $M = \_ \, mg$. 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 \( 10 \text{ parsecs} \). 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.

---

**The HRD of a few bright named stars**

![HR Diagram](image)
Lab XIV: Hubble’s Law

This is a full 2-hour laboratory exercise. It can be done in one of four ways:

1- You can do the full lab divided into two one-hour in-class sessions.
2- You may be asked to do the whole lab at home.
3- You may be asked to do a part of the lab in one hour, then finish it at home. In class, do only two galaxies, COSMOS3127341 and Arp148; do only the H\(_\alpha\) line but not the H\(_\beta\), then do the calculations with these two only. Your instructor can help with all these. Then, take your work home with you and do the measurements and all the skipped measurements and calculations at home.
4- You may be asked to do only a portion of the questions, as directed by your instructor.

The necessary pictures and spectra are provided in class, and they are also available on the web. Go to the lab web page at www.phy.olemiss.edu/Astro/Lab/Lab.html, then click on ‘Materials’, then on each of the galaxy names under ‘Hubble’s law’.

The pictures on the web have an indicator of 30 kpc size, for you to make the galaxy’s apparent diameter easier to estimate.

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 \( z = \sqrt{\frac{1}{c^2}} \). 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 \( \theta \) is its apparent size. This is nothing more sinister than the length of the arc of a circle that you might remember from 7\(^{th} \) grade, indicated on this picture, with the angle \( \theta \) in radians:

\[ D = d \times \theta \]

When you convert from radians to arc seconds, you find \( D = d \times \theta[as]/200,000 \) simply because a radian is about 200,000 arc seconds. We are assuming that our galaxies are \( D=30,000 \text{ pc} \) across, so our formula for finding the distance to a galaxy \( d = \frac{6,000 \text{ Mpc}}{\theta[as]} \) 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: ____________________________  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. $d = \frac{6,000 \text{Mpc}}{\theta_{[\text{as}]}^{\text{galaxy}}}$ means that the farther a galaxy is the _____ it looks.

3. $z = \frac{v}{c}$ 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] $\lambda_{\text{galaxy}}$</th>
<th>$\Delta \lambda$</th>
<th>$z$</th>
<th>$H_\alpha$ line [nm] $\lambda_{\text{galaxy}}$</th>
<th>$\Delta \lambda$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 3434</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4911</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5584</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COSMOS 3127341</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arp 148</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Laboratory</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></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 $H_{\beta}$ line ($H_{\beta}$ in emission), and it is redshifted. The same is true of the $H_{\alpha}$ 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 $H_{\gamma}$ and the $H_{\delta}$ 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 $H = v/d = (_______ \text{km/s}) / (500 \text{Mpc}) = _____ \text{km/s/Mpc}.$

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 $d=c/H=300,000 \text{km/s} / (____ \text{km/s/Mpc}) = ____ \text{Mpc} = ____ \text{billion ly}$. 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 H\( \alpha \) and H\( \beta \) 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 \( \sim 500 \) km/s). But then it must be an extragalactic object, and the redshift must follow Hubble’s law.

<table>
<thead>
<tr>
<th>Object</th>
<th>Apparent size [as]</th>
<th>Distance ( d ) [Mpc]</th>
<th>H( \beta ) line [nm]</th>
<th>H( \alpha ) line [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 C 273</td>
<td></td>
<td></td>
<td>( \lambda ) galaxy</td>
<td>( \Delta \lambda )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( z )</td>
<td>( \lambda ) galaxy</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>( z )</td>
<td>( v )</td>
</tr>
<tr>
<td>Laboratory</td>
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</tbody>
</table>

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 13\( ^{mg} \) 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 \( D = d \times \theta [as] / 200,000 \) 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,
\[ \Delta = 5 \times \log(d) - 5 = \ldots \text{mg}, \text{ and you’ll recall } \Delta = m - M. \] The apparent magnitude of this object is \[ m = 13\text{mg}, \] you find that the absolute magnitude of this AGN is \[ M = \ldots \text{mg}. \] (A hint: a very far-away object has to be much brighter than 13\text{mg} to shine at 13\text{mg} for us. That makes its absolute magnitude a much smaller number than 13\text{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:

**Calculate the energy output of the quasar:**
The absolute magnitude of the Sun is \[ M = 4.8\text{mg}. \] With your value of the quasar’s absolute magnitude, you know that the quasar is \[ \ldots \text{mg} \text{ brighter than the Sun} \] (take the difference). This translates to as many times as bright as \[ 10^{\text{mg}/2.5} = \ldots \text{times}. \] The Sun uses up its total mass as fuel in about 10 billion years, and compared to this the quasar will gobble up \[ \ldots \] 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? \[ \ldots \]
How close would you dare to approach a quasar? \[ \ldots \]
Lab XV: Cepheids and the Distance Ladder

Cepheids are a type of pulsating variable stars, named after the prototype δ 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 $M_V = -4^{mV}$. 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 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, $\sim 0.05^{mV}$, 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>δ Cephei</th>
<th>ζ Geminorum</th>
<th>ι 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 mas, read milli-arc-seconds. They are tiny, meaning that the stars are very far away. (1 mas = 0.001 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^h00^m00^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 $M_V=+19.3^{\text{mg}}$. 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 $M_V=+4.8^{\text{mg}}$. The absolute brightness range for stars is approximately from $-12^{\text{mg}}$ (largest supergiants) to $+16^{\text{mg}}$ (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 $\Delta = 5 \times \log \frac{d}{10}$; $\log$ 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 $\Delta$.*
This lab needs its own software called Cepheids.exe. The instructor may provide you a copy; however, it can only be installed on a Windows computer. Also, it requires copying of the Auxiliary folder into C:\Program Files\Cepheids. The extragalactic parts work only if the screen resolution is either 1920x1080 or 1920x1200. The software has been installed on the computers in the lab.

The instructor may ask you to do only certain questions and skip some if not enough time is available to do it all.

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.

3. **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?
   ___________________________________________________________________________

4. **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.
5. **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.

<table>
<thead>
<tr>
<th>δ Cep</th>
<th>___</th>
<th>___</th>
<th>___</th>
<th>___</th>
<th>___</th>
<th>___</th>
<th>___</th>
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</tr>
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<tbody>
<tr>
<td>time</td>
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</tbody>
</table>

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.

6. **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!

| ζ Gem | ___ | ___ | ___ | ___ | ___ | ___ | ___ | ___ | ___ | ___ |
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.

<table>
<thead>
<tr>
<th>Star</th>
<th>δ Cephei</th>
<th>ζ Geminorum</th>
<th>ω Carinae</th>
<th>RT Aurigae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallax ((\pi))</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>
<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>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>Distance (d)</td>
<td>pc</td>
<td>pc</td>
<td>pc</td>
<td>pc</td>
</tr>
<tr>
<td>Distance modulus ((\Delta))</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>Absolute brightness (M)</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>Dust extinction</td>
<td>0.23 mg</td>
<td>0.06 mg</td>
<td>0.52 mg</td>
<td>0.20 mg</td>
</tr>
<tr>
<td>Corrected M</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
</tr>
</tbody>
</table>

**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. \(\log P\), and since Henrietta Lewitt’s discovery we know that this logarithmic plot should put the stars on a straight line.*

---

* Lewitt used observations of many Cepheids I 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.
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

$M_V = a + b \times (\lg P - 1)$.

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 $+5\,^m$, a Cepheid is $-3\,^m$, 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>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>Absolute brightness (M)</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>Distance modulus ($\Delta$)</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
<td>mg</td>
</tr>
<tr>
<td>$\Delta$ averaged</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance (d)</td>
<td>pc</td>
<td>pc</td>
<td>pc</td>
<td>pc</td>
</tr>
<tr>
<td>Distance (d)</td>
<td>light years</td>
<td>light years</td>
<td>light years</td>
<td>light years</td>
</tr>
</tbody>
</table>

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-1a 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 $\Delta$ 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 $13.0^{m_{g}}$, 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 XVI: 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: ___________________________ 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. (If you are doing this lab remotely, the file is accessible though the lab web page https://www.phy.olemiss.edu/Astro/Lab/Lab.html by clicking “Materials” in the bottom and then “Sunspots.pdf”. The file is large, 120 Mbytes, so download is slow.)

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.

   * * *

(Note that “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?

<table>
<thead>
<tr>
<th>Sunspot A</th>
<th>Sunspot B</th>
<th>Sunspot C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>Date</td>
<td>Longitude</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td>12</td>
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</tbody>
</table>

Average daily change: ____________ Average daily change: ____________ Average daily change: ____________
Acknowledgements and copyright notices:

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

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


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

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

The laboratory web page is at
www.phy.olemiss.edu/Astro/Lab/Lab.html.
Check your grade every week on this page!

Front page: PIA20912 Blazar Artist Concept; by NASA/JPL-Caltech/GSFC

<table>
<thead>
<tr>
<th>Greek letters</th>
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<tbody>
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