Astronomy 50

Lab Manual

Union College

Spring 2015

Professors Hallenbeck & LaBrake

Astronomy 50 Lab Policies **Spring 2015**

For this course, you are required to complete five labs in three-hour sessions. Since you get Gen-Ed lab credit for AST-050, **the completion of the five labs is a requirement for the course**. For each lab you must show up, fully participate in the lab exercises, and turn in a written report. **Attendance will be taken**. In addition you will be required to attend one observatory open house. The schedule for labs and open houses is posted on the class schedule webpage, with as much notice as possible. If you have any conflicts, contact your lab instructor as soon as you know of the conflict (preferably, at least a week before the lab). If you miss a lab because of illness, contact your instructor as soon as you can and bring your instructor a note from the student health service (or whatever doctor or hospital you visited). **Please note that you cannot assume that you can just switch lab sections in a given week because the labs may not occur in parallel and because equipment is limited.**

The main goal of these labs is to teach you about the motions of the sky and several of the techniques by which the dimensions and motions of the Solar System have historically been determined. We'll find the size of and distance to the Moon, and the mass of Jupiter and an extrasolar planet (using Newton's law of gravitation). Weather permitting, there will be an outdoor observing laboratory, in which you will observe the Moon and any other bright planets visible in the evening hours. There will also be evening opportunities to observe using Union's 20-inch telescope on top of the Olin Center. Public open houses at the Observatory are scheduled regularly and will be posted on the class webpage. These events are weather-dependent: if it cloudy, they will be canceled. Check the Union College Observatory homepage for updates.
(http://www1.union.edu/wilkinf/observatory/observatory.htm or click on the link from the class homepage.)

E-mail: Evening labs may be canceled, due to weather for example, your lab instructor will send information regarding modifications to the schedule by e-mail, posts on Nexus, or on their website. If you want email sent to an account other than to your Union College account, please inform the instructor as soon as possible. Not receiving email or checking the posted lab schedule is not an excuse for missing lab, and will result in a failing lab grade.

Lab Reports: Each lab will require some written work to be handed in, and each student must hand in their own report. For some labs, only the completion of the appropriate pullout pages of the lab manual is necessary. Others may require a written report. Follow the instructions in the handouts for each lab.

Academic Honesty: Remember when you write the report, that it must be a reflection of your own knowledge and understanding. *Any report that has identical wording to another will be considered plagiarized*. In addition, if you take any material from of an *Internet source*, cite the source. Failure to do so will also be considered plagiarism.

Late Policy: Labs should be turned in by the deadline given at the time of the lab. There will be a 15% reduction in grade per day late and this includes weekends.

Note that Labs (and class activities) will count 20% towards your final course grade.

Astronomy 50, Spring 2015
Lab 4: Measurement of Mass

In this lab, you will calculate the mass of Jupiter and the mass of an extrasolar planet using established physical theories, namely the equation for circular orbits derived from Newton's Laws and Newton's Universal Law of Gravity.

## Part I: The Mass of Jupiter

In order to use the equation for circular orbits to find the mass of Jupiter, we need to measure the orbital properties of one of its satellites. This can be done from the Earth by taking a series of pictures of the Jupiter system through a telescope. By watching and measuring the motion of one of Jupiter's moons, the moon's orbital radius and period can be calculated (and from this, you can calculate Jupiter's mass). We could take these pictures ourselves using Union's telescope, but this would require at least one (preferably two) all-night observation sessions. In lieu of waiting for a clear night and staying up all night to take data, we will use computer software that simulates data taken by a telescope similar to Union's. With this software, you can watch and measure the orbital progression of each of Jupiter's Galilean moons as seen from Earth, as described below.

Procedure – The Orbit of Io
  If you look through a telescope at Jupiter, you'll see something like:

The moons appear to be lined up because we are looking edge-on to the orbital plane of the moons of Jupiter. As time goes by, the moons will move about Jupiter. While the moons move in roughly circular orbits, you can only see the perpendicular distance of the moon to the line of sight between Jupiter and the Earth (see Figure 1 and Figure 2).
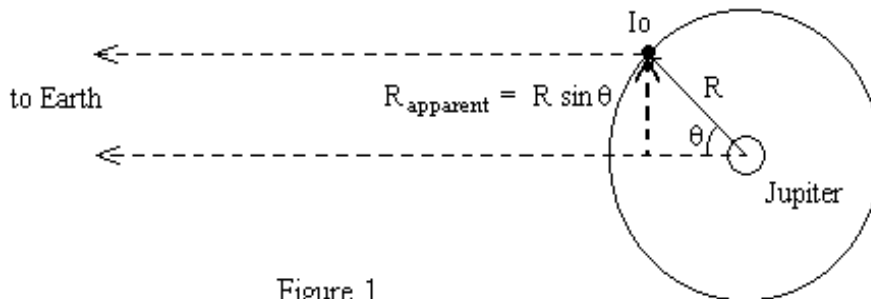
Figure 1

Therefore, the perpendicular distance of the moon should be a sinusoidal curve if you plot it versus time (see Figure 2). By taking enough measurements of the position of a moon, you can fit a sine curve to the data and determine the radius of the orbit (the amplitude of the sine curve) and the period of the orbit (the period of the sine curve). Once you know the radius and period of the orbit of the moon, you can determine the mass of Jupiter using the equation for circular orbits derived from Newton's laws of motion and Newton's Law of Universal Gravitation.

Procedure – CLEA Jupiter Software Program

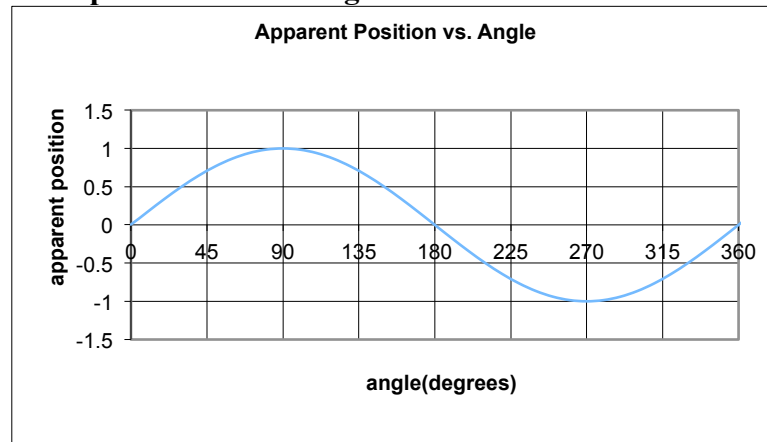**Apparent Position vs. Angle**

Figure 2: Expected variation in apparent position in time. The 0 line on the y-axis is the position of Jupiter.

The Jupiter program simulates the operation of an automatically controlled telescope with a charge-coupled device (CCD) camera that provides a digital image to a computer screen. It is realistic in all important ways, and using it will give you a good feel for how astronomers collect data from digital images. Instead of using Union's telescope and observing all night two nights in a row, the computer simulation shows the moons to you as they would appear if you were to look through a telescope at the specified time.

Instructions for using the Jupiter program
- Follow the instructor's directions to open the CLEA program.
- Select **File...LogIn** from the menu bar on the opening screen. Enter your name and your partner's name and click OK.
- Select **File...Run** from the menu bar to begin the program. Enter the start date (tonight) and time in Universal Time = Local Time plus 4 hours. Use a 24-hour clock and start at 8pm=20pm EDT, add 4 to get 0:00 UT. (UT is equivalent to Greenwich Mean Time.) Click OK.
- Before running the simulation, select **File...Timing** from the menu bar. Change the Observation Interval (Hours) to 1.00 hour and click OK.
- The display shows Jupiter and its four Galilean moons as they would appear, at the particular date and time stated in the lower left corner, seen through a telescope on Earth. We will use Io, the innermost moon. Find Io on the display by clicking on each moon. If the moon's name does not appear in the lower right corner, you did not center the cursor on the moon; try again. Keep in mind that Io, though it is the moon closest to Jupiter, does not necessarily appear closest to Jupiter on the display (why not?). You can view the display in four magnifications by clicking on the 100X, 200X, 300X, 400X buttons at the bottom of the screen. The orbit of Io is always within the field of view of the 400x magnification, so for greatest ease and accuracy of orbital measurements click on the 400X button before taking data.
- Click on Io, and note that its position on the display is given in the lower right corner under its name. The top two numbers give the X-Y position of the moon in pixels. The bottom number X is the perpendicular distance (in units of Jupiter's diameter) from the Earth-Jupiter line of sight for the selected moon as well as an E or W to signify whether it is east or west of Jupiter. Record the Universal Time and the perpendicular distance of Io

on your observation sheet, using positive numbers for measurements west of Jupiter and negative numbers for east (for example, record X=2.75E as –2.75).

- Hit **Next** to make the next measurement. Note that, as in reality, at some random times the observation will be clouded out; if this happens, just enter "clouds" on your data table for that date and time. (There is a bug in the program that may produce clouds for multiple times. If this happens, hit Next until the clouds disappear, then go back to the File...Run and change the time to the hour just after you had clouds.) When Io goes behind the disk of Jupiter (so that it is not visible from Earth), enter "behind disk" on your data table. Continue taking measurements until you hit your stop time (indicating the Sun has come up!). You've completed your first night of observations.
- Go to the next night of observations using **File...Set Observation Date**. Enter the start date and time for observation night #2, and click on OK. Take the second set of measurements.

Data Analysis

Once you have recorded data from both nights of observation, you are ready to analyze your data. The first step of the analysis is to make a plot of perpendicular distance versus time. You can choose to plot your data by hand or using Excel. Either way, it is most convenient for the analysis to plot distance versus time in hours rather than distance versus date and time. Conveniently the Hour # column of your data table is already set up; note that 24 hours pass between the start times of nights #1 and #2, so night #2 begins with hour 24.

Your plot will look something like this:
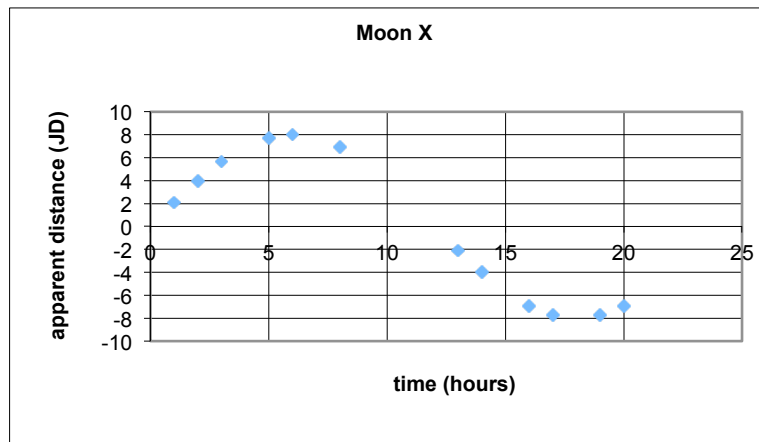
Recall the plot of Io's motion should look like a sine curve. Though your plot has a few holes in it (why?) you should still see the general shape of a sine curve. Draw on your graph (or the printout of your graph if you've used Excel) the sine curve that best fits your data. Note that since the orbital motion of Io is regular (i.e., Io does not speed up or slow down from one period to the next, and its orbital radius is constant), your sine curve should also be regular, and should be a smooth best-fit of the points.

Once your sine curve is complete, Io's orbital period and radius can be extracted from it. The period is the time it takes to return to the same point in the orbit, so on your plot it is the time between two maxima. You may find it easier to measure the time between two crossings at 0 JD; this is equal to ½ of the period. The radius of the orbit is its maximum apparent position eastward or westward. Convert the orbital period from hours into seconds.

You also need to convert the orbital radius from Jupiter diameters into meters. What quantity would you need to measure in order to determine this conversion? How might you obtain this quantity? The conversion is given on your observation sheet. Determine your orbital radius in meters and then calculate the mass of Jupiter using the equation for circular orbits (use the back of your observation sheet).

Part II: The Mass of an Extrasolar Planet

In the past few years, over 1000 possible extrasolar planetary systems have been found. It is important to realize that these extrasolar planets have not (yet) been *imaged*. Rather, we have found planets because of their effects on their host stars. Most of the first 500 planets were found because they cause their host stars to "wobble" in the sky, i.e., they show a small orbital variation in their position. This "wobble" is due to the gravitational influence of an orbiting planet(s).

In this part, you will examine actual data from observations of the star 51 Pegasi (51 Peg) made at the Lick Observatory in California. The data are the measurements of the Doppler shift of the wavelengths of the absorption lines seen in the spectra of 51 Peg. The table below lists the measured line-of-sight velocities (in m/s) as a function of time (in days). As you can see, the velocities are sometimes positive and sometimes negative, indicating that sometimes the star is receding (the velocity is positive and the wavelength is shifted to longer values) from us and sometimes the star is approaching us (the velocity is negative and the wavelength is shifted to shorter values). This variation in line-of-sight velocity was the first indication that the star 51 Peg has an invisible companion.

Observations:

TABLE 1: 51 Pegasi Radial Velocity Data

Day	v (m/s)	Day	v (m/s)	Day	v (m/s)	Day	v (m/s)
0.6	-20.2	4.7	-27.5	7.8	-31.7	10.7	56.9
0.7	-8.1	4.8	-22.7	8.6	-44.1	10.8	51
0.8	5.6	5.6	45.3	8.7	-37.1	11.7	-2.5
1.6	56.4	5.7	47.6	8.8	-35.3	11.8	-4.6
1.7	66.8	5.8	56.2	9.6	25.1	12.6	-38.5
3.6	-35.1	6.6	65.3	9.7	35.7	12.7	-48.7
3.7	-42.6	6.7	62.5	9.8	41.2	13.6	2.7
4.6	-33.5	7.7	-22.6	10.6	61.3	13.7	17.6

Note 1: The days of the observations in the table are expressed in the number of days, or fraction thereof, from when the astronomer first started observing. (The dome of the telescope was first opened at Day=0).

Note 2: The line-of-sight velocities were found from the wavelength shift of absorption lines, based on the Doppler Effect.

Data Analysis

- Use Excel or graph paper to make a plot of the data, putting the time on the x-axis and the radial velocities on the y-axis. Add labels for each axis, including the units.

- Draw a smooth best-fit curve through the points, estimating the curve in places where data are missing.

- From your graph, estimate the period of the orbit and the orbital velocity. Also estimate how accurate your determination of the period and velocity are (ask for help with this, if necessary).

In order to measure the mass of the planet, we must make some simplifying assumptions:
- (a) The orbit of the planet is circular (orbits are often close to circular).
- (b) The mass of the host star is the same as the Sun's (good approximation in this case).
- (c) The mass of the planet is much, much less than that of the star (usually true).
- (d) We are viewing the system nearly edge-on (this could significantly bias our estimate).
- (e) We express everything in terms of the mass and period of Jupiter.

We can then use the orbital velocity equation and Newton's laws of motion to derive a relationship between the orbital velocity of the star and the period and the mass of the planet. If we express this relationship in terms of the orbital velocity of the Sun (13 m/s) and the period (12 years) and mass of Jupiter, we obtain the following equation, where P is the period in years (which is the same for the star and for the planet) and v is the orbital velocity in m/s:

$$M_{planet} = \left(\frac{P}{12}\right)^{0.33} \left(\frac{v}{13}\right) M_{Jupiter}$$

To use this equation, express the period you determined from your data in years (or fraction of a year) and use the velocity in m/s. **Do not substitute your value for $M_{Jupiter}$** - your answer will then be the mass of the planet in units of the mass of Jupiter (for example $M_{planet} = 4\ M_{Jupiter}$).

Lab 4: Part I: The Mass of Jupiter   NAME:

<table>
<tr><td>Observation Night #1</td><td>Observation Night #2</td></tr>
</table>

Observation Night #1

Start: Date_____

Time_____

End: Date_____

Time_____

Observation Night #2

Start: Date_____

Time_____

End: Date_____

Time_____

	Time (UT)	Hour #	Perpendicular Distance (JD)
Observation		0	
Night #1		1	
		2	
		3	
		4	
		5	
		6	
		7	
		8	
Observation		24	
Night #2		25	
		26	
		27	
		28	
		29	
		30	
		31	
		32	

Orbital Period:_____ hrs.   Orbital Radius:_____ JD

Orbital Period:_____ sec.   Orbital Radius:_____ m

(Note: 1 JD = 1.43 x 10^8 m)

Briefly explain how you found the period and orbital radius:

What quantity did you need to convert radius from JD to m? How might you measure this quantity?

Write an equation for the mass in terms of the period and orbital radius as derived in class:

Calculation of Jupiter's mass:
(Note: $G = 6.67 \times 10^{-11}$ N-m^2/kg^2 and accepted value of Jupiter's mass $= 1.9 \times 10^{27}$ kg).

Attach your labeled graph.

Material from Part I partly extracted from CLEA Jupiter Student Manual
Material from Part II partly extracted from U.Washington Astronomy Labs

Lab 4: Part II: The Mass of an Extrasolar Planet

What period and orbital velocity did you find? Briefly explain how you determined these quantities and provide the uncertainties in your values. Attach your graph.

Show your calculation of mass of the planet:

You can also calculate the distance of the planet from the star. Since the star is assumed to have the same mass as the Sun, Kepler's 3rd law can be used:

$$P^2 = a^3 = r^3$$

where a = r because we are assuming a circular orbit. Here, P is measured in years and r is measured in AU.

The orbital radius of your planet is:

Questions:

1. Explain why there are data missing from your plots. There are at least two reasons.

2. How does your result for Jupiter's mass compare with the accepted value (give source of value)? Give reasons which might account for any possible discrepancy. (Be specific. It is not enough to say 'human error.')

3. How do your results for the mass and orbital radius of the extrasolar planet compare with accepted values (find these and provide your source)? What are possible reasons for any discrepancy?

4. (a) Considering the planet's mass, what is its likely composition? Is it more likely terrestrial or Jovian in nature? Explain.

(b) Now look at its location compared to planets in our Solar System. Where would it be located with respect to our planets if it were moved to our system?

(c) Are the properties of this planet consistent with the ideas of planetary formation we discussed in class, or are your results surprising? Explain your reasoning.