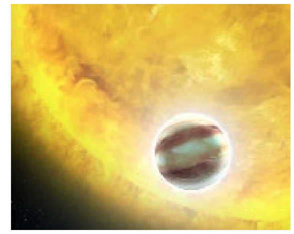
Name: ___________________________
Partner(s): ________________________
1101 or 3310: ______
Desk # _____________
Date: _____________



Wobbling Stars: The Search for Extraterrestrial Planets

Purpose

- Describe the Doppler effect for sound and light.
- Explain the relationships between the pitch, frequency and wavelength of sound.
- Describe the motion of two massive objects orbiting each other.
- Use the changes in radial velocity of a star due to its wobbling to infer the presence of a planet.

Equipment

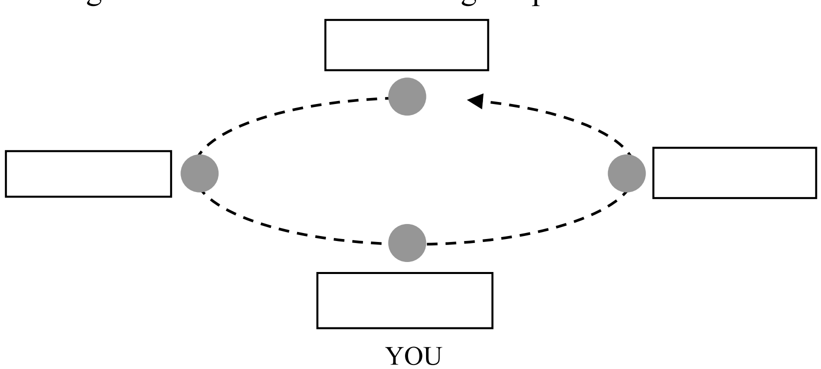
- Doppler ball
- Tuning forks (set)
- Graph paper
- Counter mass set
- Strings
- Video about Doppler effect

Are there other worlds out there resembling ours? Are there other habitable planets where living creatures, may be intelligent ones, are thriving? We can see the planets of our solar system because they reflect the light of the Sun. But we only do so at night, or we would be blinded by the Sun. So how can we detect a planet orbiting a far away Sun? We cannot just point a telescope to the suspected planet because almost all the light gathered by the mirror of the telescope would be coming from its star. In this lab, you will learn the method astronomers developed to meet that challenge. Beware: the last two parts are time consuming.

The Doppler Effect for Sound and Light

Question 1: Sound. The Doppler ball emits sound at a constant pitch. Your instructor will swing the Doppler ball in a circle above their head.

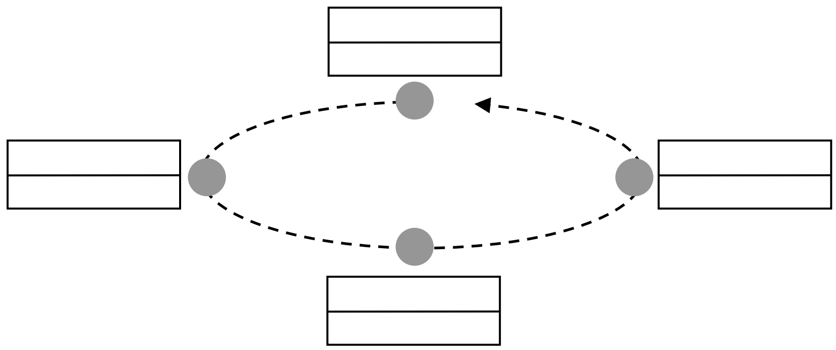
a) Fill in the following boxes with words describing the pitch of the sound emitted by the ball:



b) What does your instructor hear?

To tune their instrument, musicians use tuning forks that play middle A at a frequency of 440Hz. Any other note can also be characterized by its frequency. Look at the set of tuning forks. Each fork has its frequency written on it. Use the little hammer to hit the forks and listen to their pitch. The higher the frequency is, the higher the pitch we hear.

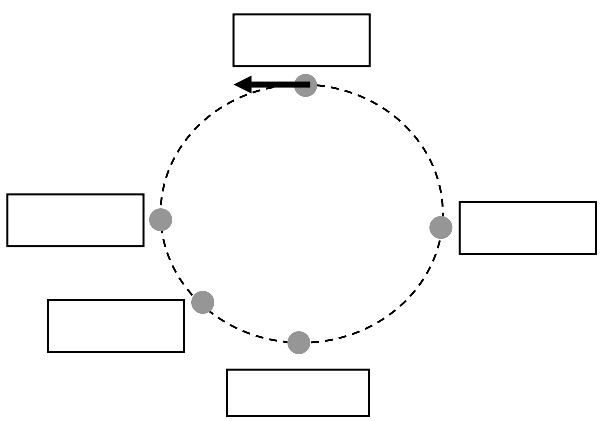
c) In the diagram below, fill in the upper box at each position with the frequency you would hear: higher frequency, lower frequency or original frequency. Then fill in the lower box with the motion of the ball: moving away, moving toward or transverse motion.



YOU

The next diagram shows a top-down view of a spinning Doppler ball. One arrow has already been drawn. The length of the arrow is proportional to the speed of the ball. We call this arrow the velocity vector of the ball. If the speed of the ball is constant, the velocity vector has the same length for any position of the ball, while the direction of the velocity vector keeps changing as the ball orbits the centre.

d) For each of the five positions on the diagram below, <u>draw an arrow</u> tangent to the path of the ball to symbolize the velocity of the ball. Note: From your point of view, when the ball moves toward you or away from you, we say that the motion is radial. When the ball is moving to your left or to your right, we say that the motion is transverse.
<u>Write down radial or transverse</u> in the box according to the direction of the ball's motion.



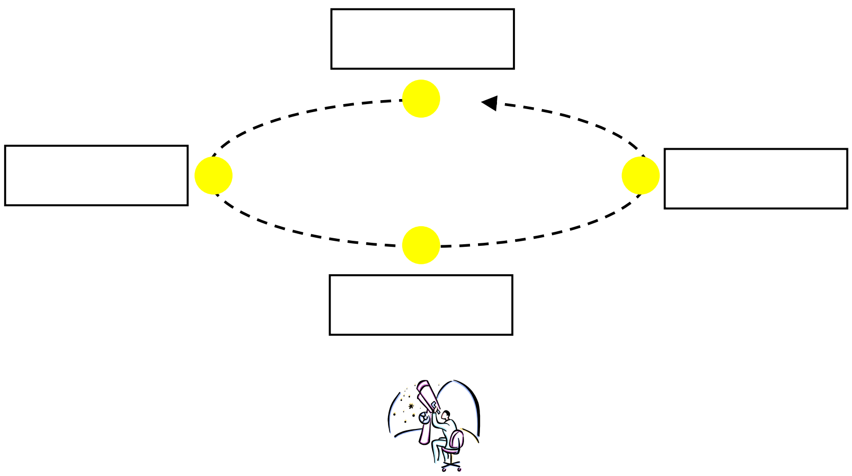
YOU

Question 2: Light. In the case of visible light, the frequency (and wavelength) of an electromagnetic wave is not related to its pitch but to its colour.

a) Fill in the following table.

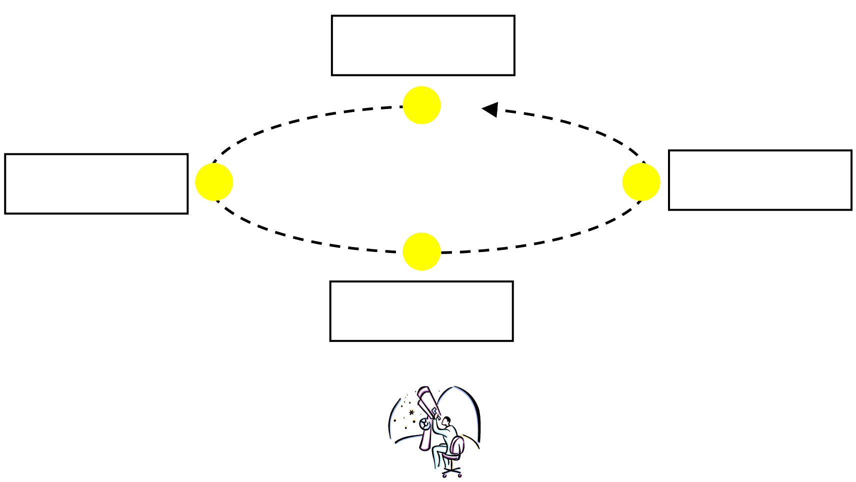
Colour	Wavelength Range (nm)	Frequency Range (Hz)
Blue		
Yellow		
Red		

b) Now instead of a Doppler ball we have a yellow star. The frequencies of light are shifted in the same manner as the frequencies of sound with the Doppler ball. Fill in the following boxes with what you would observe: yellow, blueshifted (i.e. appears bluer than normal) and redshifted.



You now observe the orbiting star through a prism that disperses the incoming light into the full range of visible wavelengths, what astronomers call the stellar spectrum. The spectrum of a star exhibits dark lines due to the absorption of certain colours by the atoms present in the atmosphere of the star.

c) Fill in the boxes to describe what happens to the wavelengths of the dark absorption lines: not shifted, blueshifted lines or redshifted lines.



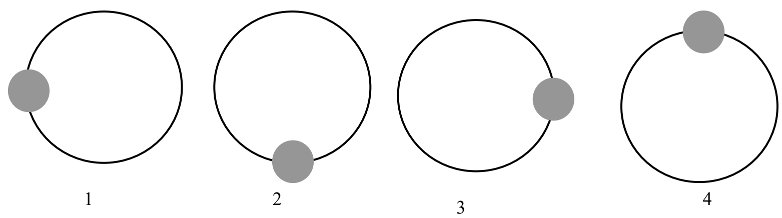
The radial velocity of a star is its velocity along the line of sight, either toward us (counted negative) or away from us (counted positive). The transverse velocity of a star is its velocity to the right (counted positive) or to the left (counted negative).

d) In each of the 4 positions in the diagram in Question 2 part (c), indicate if the observer sees a positive or negative tangential velocity, or positive or negative radial velocity.

Motion in a Binary System

Say you want to detect a massive planet orbiting a distant star. First build a model of this system, using counter masses for both the star and the planet. Instead of gravity, the bond between the two balls is the tension in a piece of string. Swing the two masses in circle. Observe how such a binary system spins.

Question 3: Two objects of the same mass orbiting each other. Complete the diagram with the position of the second mass.



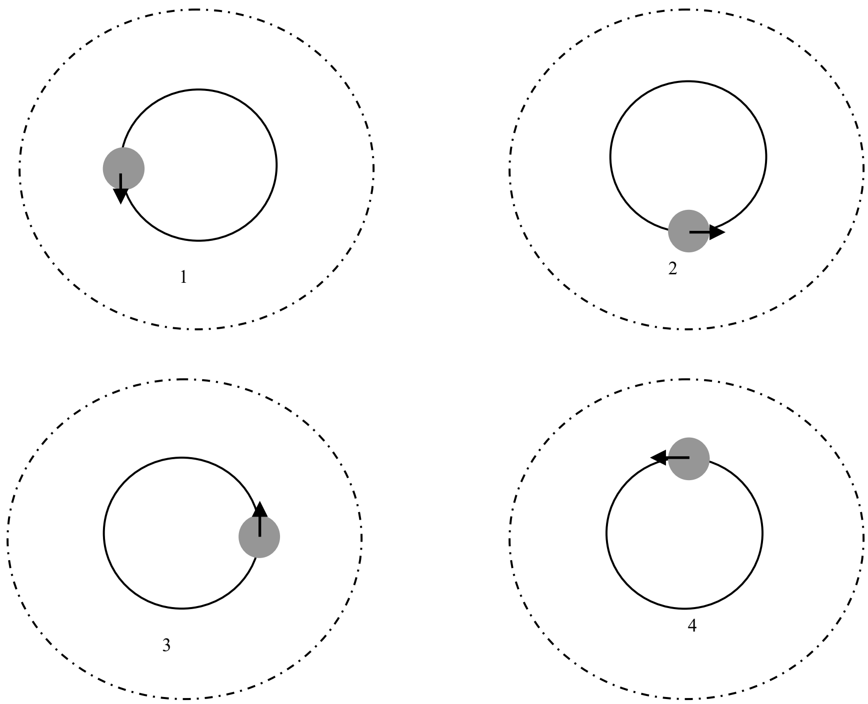
Question 4: Two objects of different masses. This would be a good model for a massive planet (a small and lighter counter mass) orbiting a star (a bigger and heavier mass). Swing the two masses in circle and see how the small lighter counter mass (the planet) orbits the big heavier one (star), while the big one (star) wobbles.

a) Does the orbit of the "planet" have a smaller or a larger radius than the orbit of the "star"? Explain.

b) Is the speed of the planet larger than/equal to/smaller than the star's speed? Explain.

c) Is the orbital period of the planet smaller than/equal to/larger than the orbital period of the star? Explain.

d) Complete the following diagram by drawing the position of the lighter object (the planet).



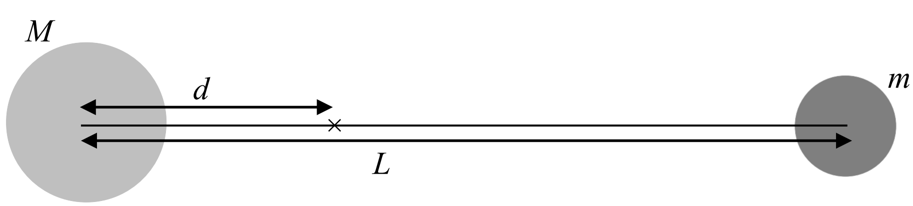
Question 5: Centre of mass. Each of the two objects orbits around the same point, named the centre of mass (CM).

a) Draw the position of the centre of mass on the previous series of diagrams (mark CM with a cross) in Question 3 & 4.

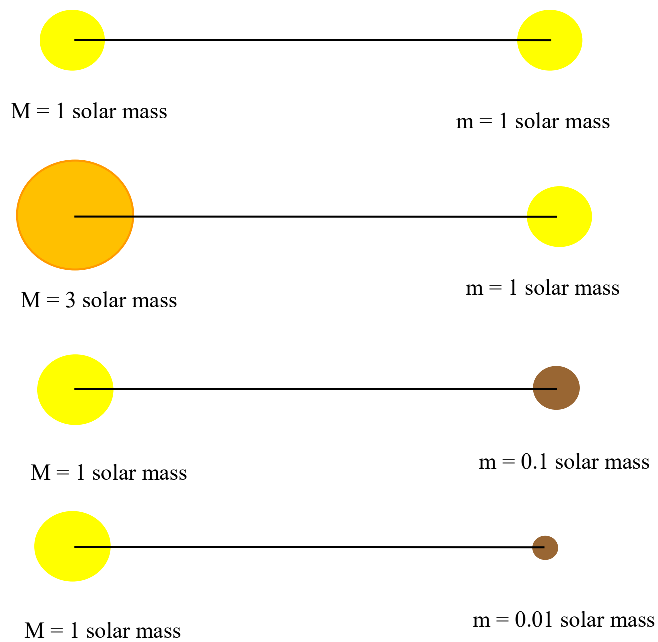
To find the distance *d* between the centre of mass of a binary system and the heavier of the two objects, we use the equation:

$$d = L \times \frac{m}{M + m}$$

where *M* and *m* are the masses of the heavy and the light objects respectively. We will express all masses in solar masses. *L* is the distance between the two objects. We see *d* is always a portion of *L*.



b) Draw the position of the centre of mass (CM) of the following binary systems (be precise, use a ruler):



c) How far is the centre of mass from the centre of the Sun in solar system? We can simplify the problem by only considering Jupiter, because Jupiter is way heavier than all the other planets. Show your calculations.

d) Is it outside or inside the Sun (the radius of the Sun is 700,000km)?

e) <u>Describe as precisely as possible</u> the motion of the Sun due to the gravitational interaction between the Sun and Jupiter (neglect all the planets but Jupiter).

A Massive Hidden Planet Makes a Star Wobble

Question 6: As a graduate student, your supervisor asks you to train on simulated data: the period of the wobbling is 16 days, the orbital speed of the star is constant: 100 m/s. You observe the star for 32 days, starting from Day 1. Using a spectroscope, you can measure the shift of the dark absorption lines in the spectrum of the star, so that you can calculate its radial velocity (*v*) of the star at any given position.

a) Predict the data set you should obtain by completing the table below.

Date	Blue shift/Red shift/no shift	Radial velocity *v* (m/s)
Day 1		-100
Day 5		
Day 9		
Day 13		
Day 17		
Day 21		
Day 25		
Day 29		
Day 33		

b) On a piece of graph paper, plot radial velocity versus time. Label the axes. Give a title to your graph. Remember that nature does not like broken lines: you curve should be smooth. Staple your graph to your lab handout.

Question 7: Discovery of the first extra solar planet. Now that you are a well-trained graduate student, you join Michel Mayor et Didier Queloz from the Geneva Observatory. For months you have been searching the sky for wobbling stars, in hope of discovering an extra solar planet. This time your target is 51 Pegasi.

a) In which constellation is that star?

b) What is the best time of the year to observe that star? (Use a celestial sphere if needed.)

You travel to the Haute Provence Observatory, in one of the nicest area of South-East France where they grow lavender and juicy olives. It is your first time using a professional telescope. The mirror is 1.93m wide. The spectrograph, the instrument that disperses the light coming from 51 Pegasi into an absorption spectrum, is named Elodie. Despite some whimsical weather, you manage to collect the following data set:

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: The days of the observations are expressed in the number of days from when the astronomer first started observing. That is, the dome of the telescope was first opened at Day = 0.

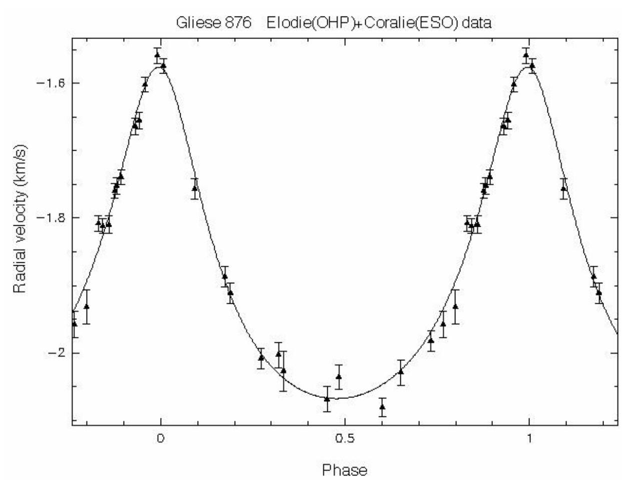
c) Graph (by hand) and analyze this data set. Show your work and comments below. And staple your graph to your lab handout.

d) Discussion. Would you infer that 51 Pegasi is in orbit with a companion planet? Justify. If so, what is the orbital period of the suspected planet?

Of course, jealous concurrent teams react heatedly to your discovery, pretending that the shift of the absorption lines are not due to the presence of an extra solar planet but to some up and down motion of material at its surface (the so called stellar oscillations). You defend your work in various conferences, but still some astronomers do not trust your methodology. One morning, a year later, while drinking your freshly brewed coffee at the SUB, you read the following paper:

Further evidence for the planet around 51 Pegasi
Authors: **Artie P. Hatzes**, **William D. Cochran**, **Eric J. Bakker**
To appear in *Nature*

The discovery of the planet around the solar-type star 51 Pegasi marked a watershed in the search for extrasolar planets. Since then seven other solar-type stars have been discovered, of which several have surprisingly short orbital periods, like the planet around 51 Peg. These planets were detected using the indirect technique of measuring variations in the Doppler shifts of lines in the spectra of the primary stars. But it is possible that oscillations of the stars themselves (or other effects) could mimic the signature of the planets, particularly around the short-period planets. The apparent lack of spectral and brightness variations, however, led to widespread acceptance that there is a planet around 51 Peg. This conclusion was challenged by the observation of systematic variations in the line profile shapes of 51 Peg, which suggested stellar oscillations. If these observations are correct, then there is no need to invoke a planet around 51 Peg to explain the data. Here we report observations of 51 Peg at a much higher spectral resolution, in which we find no evidence for systematic changes in the line shapes. The data are most consistent with a planetary companion to 51 Peg. The paper includes this graph:



Question 8: Comment on your reaction after reading the above paper.