Exoplanets Lab Guide Experiment A10

Part A: Doppler Shift

Previously we have always assumed that the center of the solar system was the sun – more specifically the very center of the sun because it was so much more massive than the planets. However, this isn't always necessarily the truth. We know that the gravitational force on any object due to another depends on the mass of both objects as well as the distance between them:

$$F_{gravity} = G\frac{M_{larger\ object}m_{smaller\ object}}{r^2} \tag{1}$$

Where *m* and *M* represent the masses, r the distance between the objects, and G is the gravitational constant. Now, let's consider the sun and the Earth. The sun exerts this gravitational force on the Earth, and due to Newtons second law (below) will cause the Earth to accelerate in some way:

$$F_{on\ object} = m_{object}a_{object} \tag{2}$$

Right now, we are unconcerned with the type of acceleration and only the magnitude of it. We can see that when $F_{gravity}=F_{on\ object}$ (meaning that the force exerted on the object is the gravitational force; the object is Earth and the force exerted on the Earth by the sun is gravity), then we find that the resulting acceleration $a_{object,\ Earth}$, is:

$$a_{object,Earth} = G\frac{M_{larger\ object,Sun}}{r^2} \tag{3}$$

Where $m_{smaller\ object,\ Earth}$ cancels out on both sides of the equation. Now, gravity works both ways! The Earth also pulls back on the sun with this same force! However, when we look to find $a_{object,\ Sun}$ by an equation very similar to equation 2, we find that:

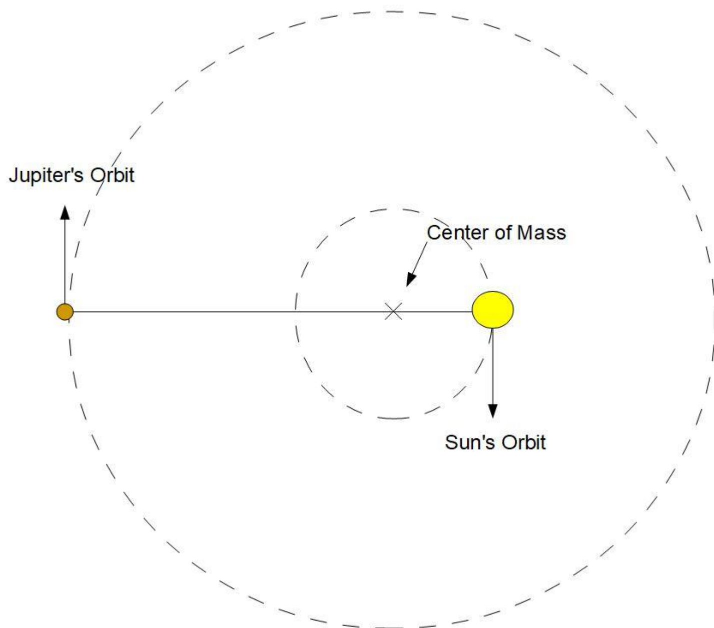
$$a_{object,Sun} = G\frac{m_{smaller\ object,Earth}}{r^2} \tag{4}$$

Let's compare equations 3 and 4 – they are both the accelerations of the Earth and Sun resulting from the gravitational influence of the other object. However, we know for sure that $M_{larger\ object,Sun} >> m_{smaller\ object,Earth}$, the mass of the sun is very much larger than that of Earth. Since the distance between the two in both equations must be the same, that means the acceleration of Earth caused by the Sun, $a_{object,\ Earth}$, is much *larger* than the acceleration of the sun caused by Earth, $a_{object,\ Sun}$ (we can see this because the numerator in $a_{object,\ Earth}$ is the mass of the sun, which is much larger than the mass of Earth as we've established). Where we have large accelerations means we have a lot of movement! And this makes sense, the Earth is definitely moving a lot in space; its moving around the sun in large circular orbits. However, though the acceleration of the sun is very small in comparison, *it is nonzero*, meaning it still causes the sun to move a little bit from it stationary position. What this results in is a slight (pretty much unnoticeable) wobble of the sun about its center point. What happens if we consider a much larger object like Jupiter? Will Jupiter's large mass cause the Sun to 'wobble' more? Actually yes, Jupiter by itself will actually cause the sun to wobble significantly around its center point.

This leads into our next discussion; what is this 'center point' I am referring to? Well, first let's forget the idea that all of the planet's orbit around the Sun who is stationary at the center of the solar system. Our new insight will be the following: *every object in the solar system will orbit around the common center-of-mass.* Between two objects, this point will lie somewhere on the line joining the two and will be located closer to the heavier object. You can imagine the planets being two objects on the ends of a long stick – the center of mass is the point where you'd put your finger in order to balance it.

Let's see what this means by looking at the **Influence of Planets on the Sun** simulation. With no planets checked off on the right, we have the sun by itself in the solar system (if there are planets checked go ahead and uncheck them all now). The green cross in the middle represents the center of mass of the system – since we have no planets added it makes sense that the center of mass is the center of the sun. Now let's check off all of the terrestrial planets (Mercury, Venus, Earth, and Mars). It'll look like nothing has happened. The mass of all the terrestrial planets together are not heavy enough compared to the sun to have a considerable effect on the center of mass, so the center of the sun is still a good approximation for the systems center of mass and thus the center of all of the terrestrial planets orbits.

Now let's uncheck all of the terrestrial planets and just check off Jupiter. Now you'll see the sun is moving considerably. The white arc represents the trajectory of the middle of the sun, and the green cross still represents the center of mass of the system. Since Jupiter is so large, the center of mass is shifted towards Jupiter a lot more than it was for the smaller terrestrial planets. As you should observe, the green cross is actually *outside* of the sun! The sun and Jupiter will both orbit THIS point, as shown in the picture below (which is exaggerated for detail).



For the Sun-Jupiter system we have here, the two objects would orbit the center of mass while always being on the line joining all three points. This means the period of each of these orbits must be the same. You can uncheck and check any other gas/ice giant planet and see a similar behavior, in these cases (checking only one at a time), the center of mass would still look to be located within the sun.

When we check multiple planets at a time, we have to now add the influence of each planet on the motion of the sun about the center of mass of the entire solar system. You'll see that the sun looks to move erotically abut the green cross – this is because each planet has a different mass and different orbit, so at any given point the sun is being tugged from all different directions at all different strengths. Sometimes all of the large planets will be at one side of the solar system and thus will drastically alter the center of mass away from the center of the sun, and other times they may be evenly placed around the solar system so that the center of mass again resides within the sun itself.

This motion about the center of mass would look to a person observing it from very far away (like on a planet orbiting a distant star) as a 'wobble' motion. This 'wobble' motion only exists due to the gravitational influence of larger planets around the star. Thus, we can also look for this motion of distant stars to find evidence of exoplanets!

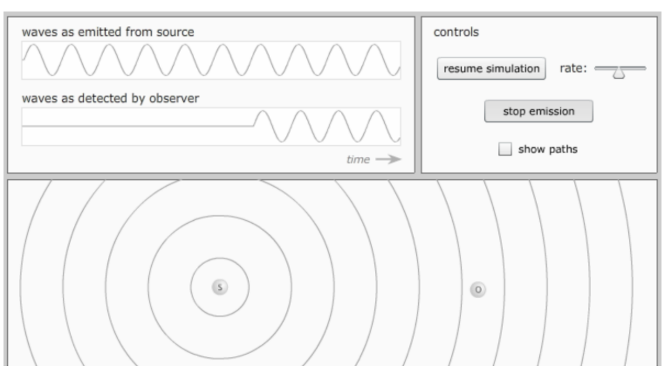
1.) **(2 points)** In our lecture above we looked at how the terrestrial planets were just too small to have any considerable influence on the sun.
2.) **(2 points)** (Note that Jovian planets are just the gas/ice giants) We saw that checking off multiple large planets causes the sun to no longer be stationary – it now will orbit the center of mass of the entire system.

3.) **(2 points)** Remember we discussed how at any given point in time the large planets are at different locations about their orbits, and so the net pull on the sun will always change with time. This causes the orbit of the sun around the center of mass to change constantly.
4.) **(2 points)** If you let the simulation run long enough you should see the white arc pass in and out of the sun many times.
5.) Now we want to look at the **Radial Velocity Graph** simulation.

This simulates us measuring the 'wobble' motion of a distant star which has a planet orbiting it. It is called "radial" velocity because we will be measuring the velocity of the distant star along our line of sight (see the green arrow that tells us that we are actually observing this system from the side – similar to how we observed the Galilean moons in our Jupiter lab). Because this exoplanet in particular is so large that the center of mass is outside the star, it will cause the star to orbit this point. This means at some points along the stars orbit around the center of mass it will be moving *towards* us, and other points it will be moving *away* form us. We measure the velocity *away* from us as being *positive*, and measure velocity *towards* us as being *negative*. This is why in the simulation as the star moves away from us in its orbit, the red dot on the plot (to the left) moves higher in the positive region. When the star moves towards us, the red dot dips below zero (becomes *negative*) and moves farther into the negative region before repeating itself.

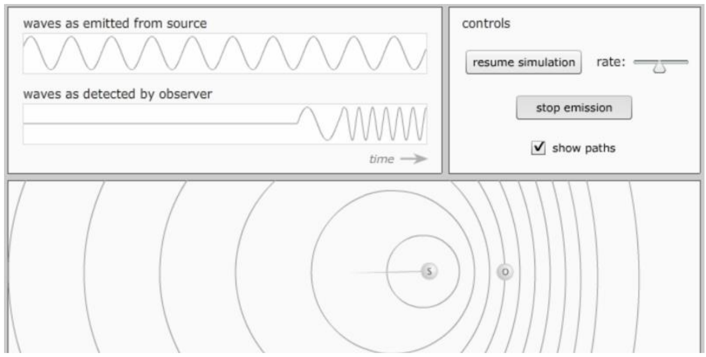
6.) **(2 points)** On the plot to the left, we can tell when the velocity is largest whenever the red dot reaches its highest AND lowest peak – these points refer to the largest *positive* and *negative* velocities. When the red dot hits these peaks, where is the star located?
7.) **(2 points)** Remember we said that the star has radial velocity when it is moving away *or towards* us. The only time it doesn't have any component of its velocity in the line of sight is when it is only moving horizontally. Also, we do not have any radial velocity when the red dot on the plot on the left is directly on the zero line (the horizontal white line). Where are the two points in which the red dot is at (or just crosses) this zero line?
8.) Now we want to look at the **Doppler Shift Demonstrator** simulation.

We are all familiar with the concept of the doppler shift, more specifically with sound. The typical example is a police siren changing pitch as it rushes towards you and again when it moves away from you. Why does this happen? Well, we know that (sound) waves move at some speed through a medium. A *source* must emit these waves. We can imagine these waves being emitted outwards in all direction from the source at the same speed everywhere. If the source is not moving, then when these waves reach a stationary *observer* (someone to listen to the sound), they are unchanged relative to how they were first emitted (this is depicted in the figure below).



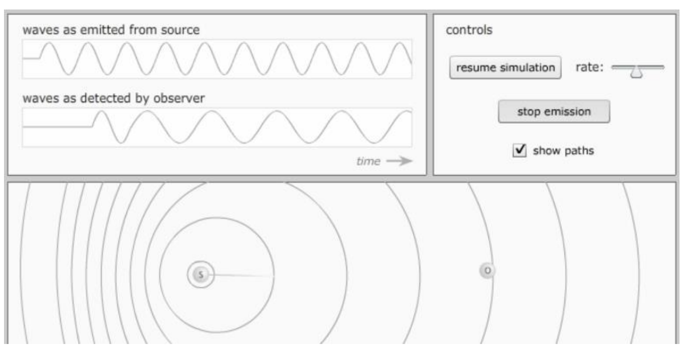
We can see that the distance between the rings (which are depicting the wave crests) are always the same everywhere and the "waves as emitted from source" have the same wavelength as the "waves as detected by observer." We have not experienced any change in pitch yet since there is no relative motion between the source and the observer.

Now let's consider the source moving towards the observer. In this case the source is still emitting waves at the same speed in all directions – the wavelength of the emitted wave is not changing. However, now we are moving in one of these directions – towards the source:



Here you can see that the source (S) is moving towards the observer (O). In front of the source, the waves look to be bunched up. This is due to the fact that every time one of these circular waves* is emitted, the source itself is closer to the rightmost portion of the previously emitted wave due to its motion. As a result, this also increases the distance between subsequent waves in the opposite direction of motion. What does this mean for the observed wave? As you can imagine from the picture above, since the waves themselves are not changing their *velocity*, a wave will reach an observer more *frequently* than in the previous example. A wave with a larger *frequen**cy*** means that it has a smaller *wavelength*. Thus, the observer will hear a sound having a smaller wavelength; a larger pitch. You can see this in the box, "waves as detected by observer." Compared to the box above it, the wave shown here is much different – the spacing between peaks (the wavelength) is much smaller and its frequency (the number of peaks received over a given time) is much larger. This is why an incoming siren seems to be at a higher pitch than normal.

Now we can imagine if the source was moving *away* from the observer. In this case the waves are now spread *farther apart*. This leads to a *decrease* in frequency and thus an increase in wavelength; a decrease in pitch. This is why a siren moving away from you will seem to be at a lower pitch than normal.



We can get similar results if we consider the source stationary and the observer moving. If the observer is moving *towards* a stationary source, then due to its motion it will 'run into' more of these circular waves,* increasing the frequency of the wave as detected by the observer and thus decreasing its wavelength; increasing the pitch. If the observer were moving *away* from the source, then it would take more time for the circular waves* to catch up to it, effectively *decreasing* the frequency and increasing the wavelength; decreasing the pitch.

* NOTE: the 'circular waves' here actually represent the multiple crests of one continuously-emitted wave – like the one seen in the top left box in the images above. Crests are the top-most peaks of the waves.

11.) **(2 points)** Since you are moving the object around (the *observer*), you need to describe what the *detected* wave looks like, i.e., the wave in the box "waves as detected by observer."

12.) **(3 points)** Now you're moving the *source* around. Look at the same box as before, do you see similar changes?

13.) **(2 points)** What this question is asking you is if you have your source and observer set up as I do in the images above (horizontally), you need to click and drag the *observer* **up and down**. In this case you should have virtually no relative motion in the direction of the source and thus there should be no change in the wavelength of the detected wave.

14.) Now we want to look at the **Extrasolar Planet Radial Velocity Demonstrator** simulation

The idea of the previous simulation was to understand that *all waves* (not just sound waves) will have some kind of Doppler effect when there is relative motion involved. This includes light (since it's a wave, too!). Since the Doppler effect will increase or decrease the wavelength of the detected wave in question, in the case of visible light this effect will cause the detected wave to be **red-shifted** (have its wavelength *increased* and thus be redder) or **blue-shifted** (have its wavelength *decreased* and thus be bluer). When an object emitting light is moving *away* from us, the light we detect will have a *longer wavelength* and thus is red shifted. If it is moving *towards* us, the light we detect will have a *shorter* wavelength and thus is blue shifted.

If you remember from our previous light lab, we discussed how we can observe the light spectra of an object to determine its composition – there are either **absorption** lines (where something has *absorbed* a certain portion of a complete rainbow spectrum) or **emission** lines (where a specific element/molecule has emitted a photon with a specific energy and thus a particular wavelength). In this simulation, we are looking at the spectra of a star that is 'wobbling' due to the presence of a large planet. As we've established in a previous simulation, this introduces a radial velocity along our line of sight – movement towards and away from us periodically. Since the star emits light, this periodic radial velocity will introduce a Doppler effect! We can measure this specific Doppler effect by looking at *emission lines*. If we assume we know what the star is composed of (which we can here), then we know *exactly* where these emission lines should be in this observed spectrum. By looking at how much the observed spectrum differs form the exact spectrum, we can determine the exact wavelength the light has been shifted. This then gives us the *speed* at which the star is moving towards or away from us. Physicists can use this to then determine the orbital properties for the star in question and ultimately find a lot more about this new exoplanet.

16.) **(3 points)** After clicking 'start animation,' you should see the emission lines move along with the motion of the star around its center of mass point. Remember that these emission lines are *red shifted* when they tend towards the redder side of the spectrum. Look to see when they tend towards this region and describe whether the planet is moving towards or away from the observer.

17.) **(4 points)** Do the same as the previous problem, but this time look for when the emission lines tend to the blue region of the spectrum.

18.) **(4 points)** Remember in question 13 there was a direction of motion in which there was no doppler effect – this was when the motion is perpendicular to the line of sight.

Part B: Transit Method

The previous section was all about how, from the "wobble" motion of a star due to an exoplanet, we could detect the change in wavelength of light from a star (due to the Doppler effect) in order to find its relative velocity and thus many of its orbital parameters (including those of the exoplanet, which we care more about in this situation). In this section we will look at another way of detecting an exoplanet – the transit method. As the name suggests, when an exoplanet *transits* in between us and the star, it blocks some of the light from that star. If we are looking at this star in question, at this time there is a measurable change in the *brightness* of the star. The amount of change and the length of time over which this decrease persists depends upon the exoplanet's properties and orbital parameters.

In the **Transit Simulator** in NAAP labs you will be playing around with some of these parameters to see which planets are easiest to find with this method.

3.) For this question you are seeing how changing the parameters of the exoplanet affects the depth and duration of the eclipse (the exoplanet crossing in front of the star. The depth is how low the dip in the upper right plot goes (i.e., if “1” means 100% of the light from the star is being observed, then anything less than that means we are not observing all of the light. Obviously, this is because the planet is blocking it). Since the horizontal axis represents time, the width of this dip represents how long it takes for the planet to transit across the planet – the duration can be found right underneath the plot where it says, ‘eclipse takes…’. **(a) (4 points)** We can change the planets radius in the lower left box; ‘planet properties.’ What does this do to the depth and duration? **(b) (4 points)** Same place as the radius, what happens when this increases? **(c) (4 points)** Notice you are looking at how the mass of the *star* affects this graph. This can be changed in the ‘star properties’ box at the bottom. **(d) (4 points)** Inclination can be changed in the ‘system orientation and phase’ box in the lower right. Note that if the orbit is inclined too much from our line of sight, the planet will never cross between us and the star! Thus, at what inclinations do you actually see some dip in the plot? When do you start to see none at all?

4.) You need to make sure to have option B chosen (and click set) in the ‘presets’ box. Then in the box with the plot you need to click the ‘show simulated measurements’ and enter 0.00002 into the ‘noise’ box. This is similar to us trying to observe an Earth-like exoplanet orbiting a distant star.

5.) **(4 points)** To determine whether Kepler can actually detect an Earth-like exoplanet like this, it needs to be able to pick up a very slight dip in the normalized flux. When we make the changes in question 4 above, can you discern a clear dip in the data in the plot? If you can see a clear dip in the data, then Kepler should be able to detect this planet.

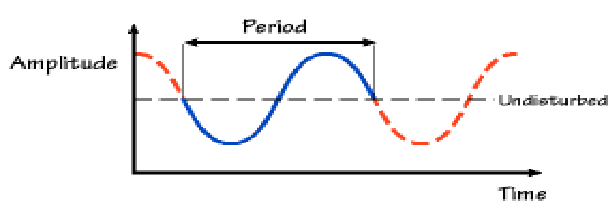
6.) **(2 points)** You need to look for the eclipse duration which can be found right underneath the plot. Note that this should only take a few *hours.*

7.) **(2 points)** Remember these exoplanets are, themselves, orbiting their star in circular orbits. When they end up between us and their star, that is only at a specific point along their orbit. In order for them to get back to this point, they need to travel back around in their orbit to the same point again. Thus, it will take one period between eclipses – this can also be found right underneath the plot next to where you found how long the eclipse itself takes.

8.) **(6 points)** We are interested in observing stars, right? When do we see a sky full of stars – not during the daytime of course…

Part C: 51 Pegasi - Discovery of a New Planet

This section will have us go through the analytical process similar to that done by the astronomers who discovered the first planet orbiting around another star; 51 Pegasi b. Our goal is to find the mass and semi-major axis of this exoplanet just by observing the radial velocity of its host star. All we need to start is the data provided in the plot in the lab manual – the data points (large black dots) represent the measurements taken by these astronomers of the star 51 Pegasi. The solid sinusoidal (wave) line going through them is a ‘fit,’ meaning that a computer program took a function that described these black data points better than any other function and plotted it. This line, then, is the line in which we would predict most of our data points would lie if we continued to measure this star.



1.) **(2 points)** The image above describes what exactly one *period* is for a wave. We see that from the starting point (the beginning of the blue line), it goes through one full downward motion and one full upward motion before coming back to the starting location – this describes a full period. From this point, the wave will continue to repeat itself. Now we need to look at the plot in the lab manual and see just how many full periods are represented here. Lets start at the very left-hand side. From this starting location we go downwards until we start going back upwards again. We then hit the tallest peak and go back downwards again until about TIME = 6 days where we arrive at the same point (on the y axis) at which we started. This is one full period: one full **cycle**. We need to use this logic to find how many FULL CYCLES are represented here. HINT, you should be getting less than 10 full cycles if you are doing it correctly!

2.) **(2 points)** At the beginning of the section (and in question 1), we are told that these observations were taken over **33 days**. We found the *number of full periods* in question 1, now we need to determine how many *days* each period lasted. We can take the total number of days **divided by** the number of full cycles.

3.) **(2 points)** You found the period in *days* in question 2, now you need to find it in *years.* All you need to do is convert this amount of days (form question 2) to years. This is obviously going to be a very small number since you only have a handful of days. To find this number, you have to divide the number of days you got in question 2 by the number of days in one year.

4.) **(4 points)** Think of question 8 in the previous section – what are we most limited by in our observations of stars **in the night sky**?

5.) **(2 points)** Here, I want you to use the exact value given to you. If you look in the picture of the plot you can see in the top right-hand corner that **K=56.83 m/s**.

6.) **(6 points)** Using the period you found (in *years*) and the K you just found (in m/s), you can now find the *ratio of this exoplanets mass with that of Jupiter* using the equation given to you.

$$\frac{M_{planet}}{M_{Jupiter}} = \left(\frac{P}{12}\right)^{1/3} \times \left(\frac{K}{13}\right) \qquad 5$$

Note that plugging in P and K into the right-hand side will give you a result that is *equal to* $M_{planet}/M_{Jupiter}$. If you multiply both sides by this $M_{Jupiter}$, you will get the mass of this exoplanet, M_{planet}, written as some fraction of the mass of Jupiter (this is how you will want to write it for question 8 for completeness.

7.) **(4 points)** If you remember form our introductory discussion, if a distant star and single large planet are orbiting the common center of mass, the periods of **both** orbits must be the same. In this case, we are assuming that this exoplanet is the only object influencing this distant star, and thus the period we calculated for the star in question 3 *is the same as the period for the planet*. However, we can still use Kepler's third law (and all of its approximations) to get a good idea of the orbital properties of the system. Thus, we can find the **semi-major axis, a,** by using:

$$\sqrt[3]{P^2} = a$$

If P is in *years*, then a here will be in AU's.

8.) **(8 points)** Using the radial velocity data given to you, you have predicted the mass of this exoplanet (question 6 as some fraction of the mass of Jupiter), the period of the exoplanet (question 3 in years), the amplitude K (which we decided to take as the exact value in question 5), and the semi-major axis of the exoplanet (question 7). Your job in question 8 is to compare all these values you have found to the actual values by using the percent difference formula:

$$PercentDifference = \left|\frac{Calculated\ Value\ -\ Actual\ Value}{Actual\ Value}\right| \times 100\% \qquad 6$$

9.) **(4 points)** You have found the semi-major axis, a, of this exoplanet in AU's. You should have noticed this is less than 1, meaning that it is closer to its host star than Earth is to our sun! If you did everything correctly, actually, you should see that this value is actually less than 0.4 AU – meaning it is closer to its host star than Mercury is to our sun! You need to insert a circle/image representing, if this planet was in our solar system, where it would be in relation to the rest of the planets in our solar system.

10.) **(6 points)** What you need to realize here is first, this planet is super close to its host star (which we predict it to be similar in size to our own sun). What is most astounding is considering the *mass* of this planet. The mass of this planet is roughly half of that of Jupiter, which is still considerable large and definitely a gas giant. However, in our solar system all the large gas giants are very far from the sun – since we only have had our solar system to observe at the time they discovered this exoplanet, it was considered fact that these types of planets could only form and exist at these large distances from their host star. This discovery disproved that idea, since it was evidence that a large (gas giant) planet could form and exist at distances super close to its star. Exoplanets like these are called ***hot Jupiters*****,** since they can be as large (or larger) than Jupiter and have very small semi-major axes.

11.) **(2 points)** From what we have already discussed about this planet, it should be easy to discern what kind of environment this exoplanet would have.