<u>Exoplanet Detection Lab Part 2:</u>
Investigate Further Using the Extrasolar Planets Encyclopedia

Go to www.exoplanet.eu and click on "Interactive Catalog". This website is a compilation of ALL of the data on EVERY (confirmed/reliable) detected exoplanet found using ANY detection method. This represents EVERYTHING we know about all of the exoplanets we've detected so far, and the list is constantly updated. Using the information on this page, calculate the total number of exoplanets (not exoplanetary systems) detected so far

Total number of exoplanets:

Now, calculate what percentage of the TOTAL detected exoplanets fall into each of the following categories (show your work):

Detected via radial velocity:

Detected via transits:

Detected via microlensing:

Planets in multiple planet systems:

Now, go to the competing site, www.exoplanets.org and click on the "Plotter" link. This brings you to a table with all of the known parameters of these exoplanets. Click on "Histogram Plot". This function will gather all of the information about any parameter you're interested in about these planets and create a histogram for you.

Play around with this interface for a while and figure out how it works by selecting different parameters in the "Data" dropdown menu and playing with the other settings. Then, answer the following questions.

What is a histogram? Specifically (a) what does it show? (b) what do the x and y axes represent?

How does the histogram change if you select “Raw Counts” vs. “Probability” for the Normalization?

Describe what happens when you change the number of “bins”.

Describe what happens if you make the bins “logarithmic”.

Now, make a histogram of planet mass by selecting “msini” in the data dropdown menu. Note that you can rescale the x-axis under the “Advanced” tab. By entering 0 for the “Min.” and 10 for the “Max”, and dragging the number of bins to 10, you’ll get a graph that is easier to read.

How many planets are in “bin 1” with a Jupiter mass or less?

Now click the “Add Filter” option. There should be a dropdown menu that says “Filter”. Go there and select “RV Planets”. This changes the planets that make up the histogram by selecting only those that were detected using the radial velocity method. You will be using this filter throughout the rest of the investigation, but it will be erased whenever you leave or refresh the page so check periodically to make sure it’s still “on”.

<u>Now</u> how many planets are in “bin 1” with a Jupiter mass or less? Did it change from the last question?

Looking at the entire histogram, what does it seem to tell you about the population of planets that are detected by radial velocity?

What percentage of the total RV planets have masses greater than that of Jupiter? (Note: you need to include those with more than 10 Jupiter masses as well, which are currently off the end of your histogram). Do this by adjusting the min and max. You will also need to read the graph to estimate the number of planets in each bin.

Greater than 5 Jupiters?

Greater than 10 Jupiters?

Earth's mass is about three-thousandths of the mass of Jupiter. Manipulate the min/max and number of bins to find out how many RV planets have Earth masses or lighter.

____________ RV planets have masses less than the mass of Earth.

____________ RV planets are 10 Earth masses or lighter.

Planets with greater than 10 earth masses are unlikely to be rocky "terrestrial" planets. What percentage of the total RV planets fall into the category of possible terrestrial planets? Show your work below.

Go back to the main exoplanets.org page and click on the "Table". When you get there, add a filter to give you only RV exoplanets. Then click on the column label for the second column (M[sini]) which will sort the known RV planets by their masses from smallest to largest (actually, it's important to note here that it will sort them by our best estimate of their masses – since the system has an unknown inclination to our line of sight, there is some uncertainty in this value).

If you scroll and look at the masses of the smallest planets, many of their names begin with "Kepler", which is the name of the NASA mission that is currently searching for extrasolar planets via the transit method that you learned about in the Exoplanet Detection Lab: Part 1. This tells you that many transiting exoplanets can ALSO be detected using the radial velocity method.

Why are the RV and transit methods likely to pick up the same systems? (hint: think geometry!)

If you look at the second and third columns in the table, you'll find that while all of the RV planets have estimated masses, ***only some of them have radius values in the table****. These radius estimates were NOT determined from the RV data, but through transit data, so these are the planets on the list that have been detected by both methods.*

Why can you determine an exoplanet's mass, but not it's radius with the radial velocity method? Hint: what causes a star to "wobble"?

Why can you determine an exoplanet's radius, but not it's mass with the transit method?

As you may be able to imagine, it is highly useful to have BOTH RV (mass) and transit (radius) data for an exoplanet. **What property** of these planets can we determine if we have both an RV and a transit detection of the same planet that we can't determine with each method alone **and why might this property be useful** in distinguishing between rocky terrestrial planets and gas giant "Jovian" planets?

Now, go back to the first page and click on "Plotter", but this time stay in the "scatter plot". This convenient feature will allow you to plot one property of all of the RV exoplanets versus another property, allowing you to see whether they are "correlated" (related to each other such that, for example, one increases when the other increases or vice versa). There are lots of interesting things that we could investigate here. Let's begin by investigating how radial velocity technology has improved with time. Make sure that your "filter" for only planets detected by RV is still active.

First, ***set your x-axis value to "Date"*** *using the dropdown menu. historical note: although the first planet detection that was confirmed by independent groups was in 1995, the exoplanet around Gamma Cephei that was detected in 1988 by a group of Canadian astronomers was eventually confirmed in 2002, so it is technically the "first" exoplanet discovered via the radial velocity technique.*

Two things to note as you do this part of the investigation:

(1) You can change the minimum and maximum values of the axes simply by dragging them up or down, left or right. This may help you to answer some of the questions/better understand some of the data.

(2) This tool will almost always choose to plot the data logarithmically (which means it gets sorted by power of ten, or "order of magnitude"). You can make the scale linear instead under the "advanced" tab by unclicking "log" next to the X and Y settings. This is another thing that you might wish to do to get a handle on the data.

Begin by choosing "planet period" for the y-axis value. What sorts of planet periods does this diagram suggest are easiest to detect by the RV method?

Can you find a trend in the diagram with time? How are the planet periods we're detecting changing with time?

What does this tell you about how radial velocity technology has improved with time? Why were some planets found earlier than others?

Under "colorscale" choose "transit depth". For our purposes, we will just consider that now all of the planets discovered FIRST via the radial velocity method and then later discovered to <u>also transit</u> their host star are now shown.

Roughly what percentage of RV-detected planets also have detectable transits? Explain how you made this estimate.

Where are they concentrated on the diagram and what does this mean in terms of their physical parameters?

This is not a selection effect! <u>**Why**</u> are there no transiting planets in the other portion of the diagram?

Now, leave the x-axis scale the same, but manipulate the dropdown menu and the y-axis scale to answer the following questions.

What trend is revealed if you examine how the *masses* of RV-detected (make sure this filter is still on) planets have changed as technology improved with time?

Click on some of the points in the diagram with both high masses and low masses and examine the actual RV curve that appears. What about the RV curve changes as the planets get smaller and why does this make them more difficult to detect?

Now, change your y-axis to investigate the trend in the semi-major axis of RV-detected planets with time. What trend is revealed?

This plot should be very similar to one of the other two you just examined. Which? Why are these quantities related?

Summarize your findings by circling the appropriate choices in the following statement:

As radial velocity technology improved, we were able to find planets with (lower/higher/both) masses in (closer/farther) orbits and with (shorter/longer) orbital periods.

Now, plot planet semi-major axis on the x-axis and planet mass on the y-axis. Manipulate the axes to cut out any outliers and give you a better picture of what's going on with the majority of the detected planets. Sketch the graph that you created on a separate piece of paper and attach it to this lab. Use logarithmic graph paper, which you'll find at the end of this lab.

Where are most of the planets in your plot? (drag the axes to get a better sense for this) Where are they clustered?

Do their masses and semi-major axes seem to jive with what you already know about our own solar system (where we see small, rocky terrestrial planets in the inner solar system and large, gassy Jovian planets in the outer solar system)? Why or why not?

If you really want to put these planets into the context of our own solar system, let's set the parameters to match. Set the y-axis maximum value to 1 Jupiter mass (the most massive planet in our solar system) and the x-axis maximum value to 30AU (the distance to Neptune in our solar system) Sketch the plot you see on a separate sheet of logarithmic graph paper and add in any of the planets from our own solar system.

Planet	Distance (in AU)	Mass (in Jupiter Masses)
Jupiter	5	1
Saturn	10	.3
Uranus	20	.05
Neptune	30	.05

Are any of the RV exoplanets in similar locations to the Gas Giant planets of our own solar system according to your graph? If not, how are they generally different?

Here are the data for the terrestrial planets in our solar system. Add these in as well.

Planet	Distance (in AU)	Mass (in Jupiter Masses)
Mercury	0.4	.0002
Venus	0.7	.003
Earth	1	.003
Mars	1.5	.0003

Are there any planets like Venus or Mercury among the planets you find in the plot? Cite some data about the planets that you find in that region to support your argument.

Together with your lab partners, develop two more questions that you might investigate using this tool. These should not be direct offshoots of the questions you've already answered. This tool is very versatile and can answer all kinds of questions that you haven't thought of yet!