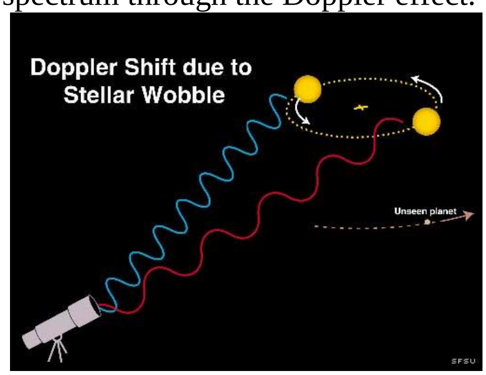
Searching for Extra-Solar Planets

Until 1996, astronomers only knew about planets orbiting our sun. Though other planetary systems were suspected to exist, none had been found. Now, thirteen years later, the search for planets around other stars, known as extra-solar planets or exoplanets, is one of the hot research areas in astronomy. As of June 2011, 560 extra-solar planets have been found in at least 369 planetary systems. So far, most of these planets are Jupiter-sized and larger, but as observational search methods improve, astronomers are finding planets of smaller sizes. With the launch of *Kepler* in 2009, astronomers hope to begin finding Earth-like planets, a quest that will continue with several more satellite telescopes within the next ten years.

Part I: The Radial Velocity, or Doppler Wobble Method

More than 90% of the known extra-solar planet candidates have been discovered through the radial velocity, or Doppler wobble method. In this method, a planet (of relatively low mass) tugs on its heavier parent star as the two bodies orbit around their common center of mass. The tiny shifts in the star's motion can't be observed directly, but instead they are revealed in the star's spectrum through the Doppler effect.



Caption: A star and planet system showing how the star orbits around the center of mass of the system, causing its light to be shifted due to the Doppler effect (the star's orbit is greatly exaggerated here).

1. With a sketch, show how two of the Balmer absorption lines, at 656 nm and 486 nm, would appear if four equally spaced observations were made in one complete cycle of the star's motion. (Be sure to show the direction of the observer in your sketch.)

2. By measuring wavelength shifts in the star's spectrum, astronomers can determine the orbital parameters of the star and planet system, and estimate the mass of the planet. Note that precision spectroscopy is necessary. If observed from outside the solar system, the planet Jupiter would cause a shift in the sun's spectrum of about 12 m/s. This is not much above the best errors in the method, which are now down to about 3-5 m/s.

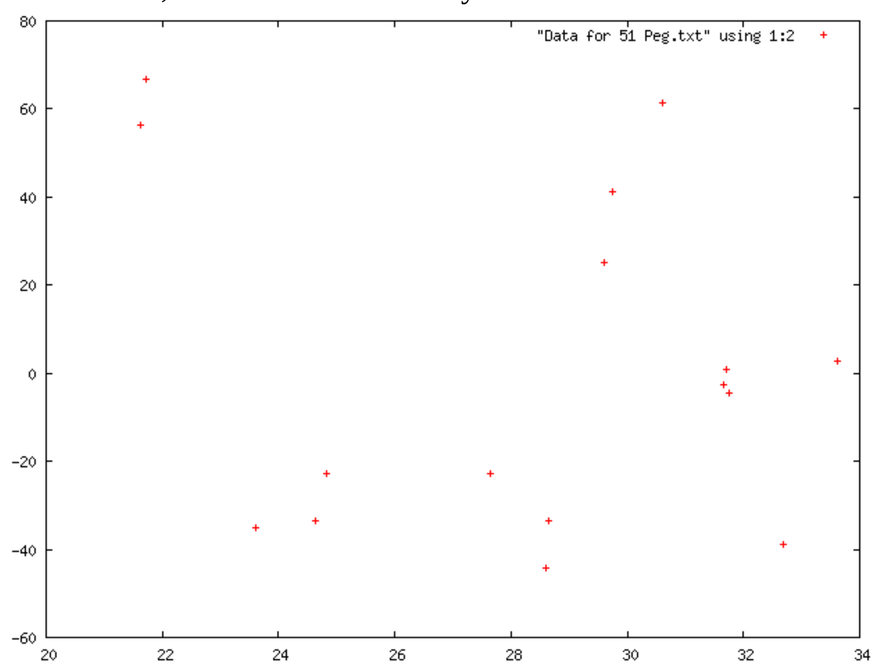
The star and the planet are each orbiting around the center of mass of the star+planet system. Suppose you observe the star regularly over the course of a few years, which turns out to be long enough for at least one planet orbit. How do you expect the velocities of the star to change? That is, if you plot velocity vs. date, what do you expect to see if a planet is perturbing its star? Draw a sketch of what you expect over one orbital period.

3. Once we've collected data for 51 Pegasus from the telescope, compiled in Table 1 below, the first thing to do is look at it by plotting the date on the x-axis and the velocities on the y-axis.

Table 1: Data for 51 Peg

Date (JD-2450000)	Velocity (m/s)	Uncertainty (m/s)	Phased Date
21.62	56.4	4.5	1.62
21.71	66.8	6.4	1.72
23.60	-35.1	5.1	
24.64	-33.5	2.6	0.44
24.82	-22.7	3.7	
27.65	-22.7	4.3	
28.61	-44.1	4.7	0.21
28.66	-33.6	4.8	0.26
29.61	25.1	4.3	
29.75	41.1	4.3	
30.60	61.3	5.6	2.25
31.66	-2.5	5.0	
31.71	0.8	5.7	3.31
31.75	-4.6	5.9	
32.69	-38.8	4.7	
33.61	2.7	4.4	1.01

To save time, we have done this for you:



4. Describe this graph. Is it different from your expectations? Why? Can you conclude that there is or isn't a planet present? Can you put any upper or lower limits on the orbital period of a possible planet?

5. Astronomers use an iterative method to estimate the period of the planet that best fits all the data. The method involves folding the data over itself, or wrapping it, so that the complete data set represents one orbital cycle. For 51 Peg, the estimated period is 4.2 days. Fill in the Phased Date column in Table 1 in the following way. We want all the Phased Date values to be between

0.0 and 4.2. Suppose our data starts at day 20. Subtract 20 from the first few dates and enter them in the Phased Date column. Continue down the column with the following adjustment: if any Phased Date is greater than 4.2, subtract an additional 4.2 from that date. So, after a while, you'll be subtracting 24.2, then 28.4. We have filled in several phased dates already for you to help provide a check.

a. Plot the Phased Date (x-axis) vs. the velocities (y-axis). You should be able to draw a sinusoidal curve through the result.

b. Compare the period of 51 Peg's planet to the period of Mercury around the sun.

6. To estimate the mass of the planet, you need to know its period, semi-major axis and its velocity around the star, together with the radial velocity of the star. We will calculate these step by step below.

It turns out that 51 Peg is about the same mass as the sun so to measure the semi-major axis, we can use Kepler's 3^{rd} Law (without Newton's modification). If the period is measured in years, then we obtain the semi-major axis in A.U. from $P^2 = a^3$.

a. Calculate the semi-major axis, a, of the planet around 51 Peg.

We can obtain the circular velocity of the planet, v_{planet}, with its distance from the star and its period: v_{planet}=distance/time = $2\pi a/P$.

b. Calculate the velocity of the planet, v_{planet}, in m/s.

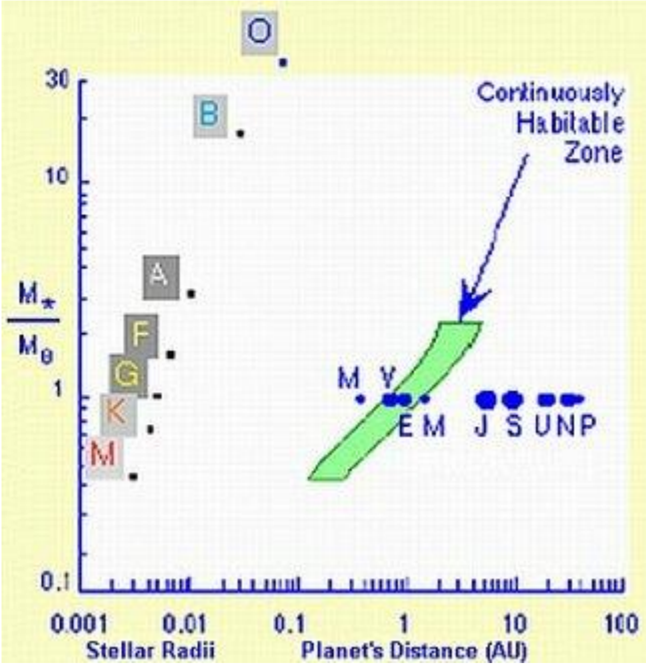
Because this is a simple center of mass problem, the masses of the star and planet are inversely proportional to their circular velocities:
$M_{planet}/M_{star}=v_{star}/v_{planet}$

The circular velocity of 51 Peg can be found from your second graph as half of the difference between the maximum and minimum velocities.

c. Determine the velocity of 51 Peg, v_{star}, from your graph. Use this to calculate the mass of the planet, M_{planet}

d.For scale, convert your mass to Jupiter masses ($M_J=1.90\text{x}10^{27}$ kg) and to Earth masses ($M_E=5.97\text{x}10^{24}$ kg)

7. Where does your planet fall on a plot that shows potentially habitable planets?



Caption: The mass of the star in solar masses is plotted against the distance the exoplanet is from the star. Note that the radii of stars of different spectral types are also indicated by the corresponding letters (O, B, A, F, G, K, M). These letters show the location of the zero subdivision of each spectral type, thus F5, for example, is between F0 and G0 (and not between A0 and F0). The approximate size and position of the planets of our solar system are shown along the horizontal line corresponding to a star with one solar mass (the Sun) and are labeled by the first letter of their names. [Richard Bowman, David Koch, Kasting et al. (1993).

Note that both scales are logarithmic. For example, the vertical scale is read as 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7. 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 20 and 30.

The habitable zone is defined by where one would expect to find liquid water in that solar system.

a. Does 51 Peg's planet fall within the continuously habitable zone?

8. Repeat questions 3 to 7 for HD 10697, whose data is given in Table 2. Because of the spacing of the dates, your first graph will be sufficient (you won't need to calculate and graph the phased dates in question 4). You can determine the period of the planet from the graph. HD 10697 is 10% more massive than the sun but you can ignore this complication.

Table 2: Data for HD10697 = 109 Psc

JD - 2450000	Velocity (m/s)	Uncertainty (m/s)
367	-63.0	2.8
461	-98.8	4.2
715	-125.1	3.0
716	-134.8	2.8
806	-62.2	4.5

837	-49.8	5.1
839	-51.0	4.6
983	20.6	2.6
1013	29.5	3.0
1014	31.5	2.7
1044	40.7	2.9
1051	44.8	2.7
1068	57.3	2.9
1070	55.5	2.8
1072	51.5	3.1
1075	59.0	2.6
1170	75.7	4.1
1342	24.9	3.1
1343	28.0	2.7
1368	5.0	3.1
1374	0.0	3.0
1410	-25.3	2.9
1412	-34.7	3.2
1438	-56.6	3.1
1439	-53.0	3.0
1440	-46.9	3.2
1487	-111.4	3.7
1488	-97.2	3.7

a. Compare this planet to that of 51 Peg. Note that you need to calculate the period and semi-major axis of the planet, as well as the velocities of the planet and star before you can determine the planet's mass and make this comparison.

9. Use the minimum error of 3 m/s to calculate how small of a planet mass you could detect for stars like 51 Peg and HD 10697. Could you detect Earth-like planets for either star? (Hint: suppose the velocity of the star was 3 m/s, what mass of planet would you detect?)

10a. The planet around 51 Peg is thought to have a mass of 0.468 x M_{Jup} while the planet around HD10697 is thought to have a mass of 6.12 x M_{Jup}. Calculate the percent errors in your measured masses of each planet.
Note that percent error = ((your value – true value)/true value)*100.

10b. On two side-by-side scaled drawing with the orbits of the inner planets and Jupiter (circular orbits will suffice), show the orbits of these two planets.