ASTRO 1050 - Fall 2012
LAB #6: Extrasolar Planets

ABSTRACT

This is an exciting time in astronomy. Over the past two decades we have begun to indirectly detect planets that orbit stars other than our sun. Methods of detection range from systematically observing the light curve of a star, gravitational lensing, to direct observation of an extrasolar planet. To distinguish these planets from the eight familiar planets of the solar system, we call them extrasolar planets. The stars around which the planets orbit are not too different from the sun. They are nearby, often fairly bright, and some of them have been in star catalogs for centuries. In this lab we will take an in-depth look at the doppler shift-method.

Materials

Calculator, computer

Introduction

When a planet orbits around its star, the star does not remain perfectly still. There is an appreciable reflex motion of the star caused by the mutual gravitational pull of the planet-star system. In figure 1 a small planet is connected to its heavier parent star (by a line in the diagram, but by the force of gravity in reality). They orbit about each other, but at the same time both are traveling on a path through space. The center of mass (C.O.M.) of the system travels on a straight line (the small dotted line) in the below figure. Most of the time, the planet is invisible to an observer.

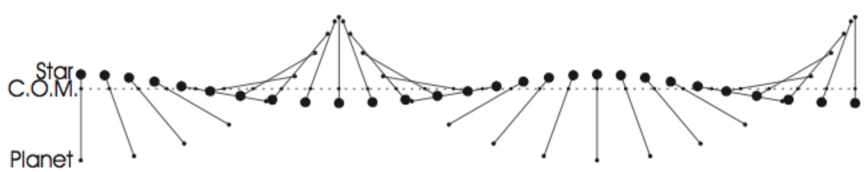


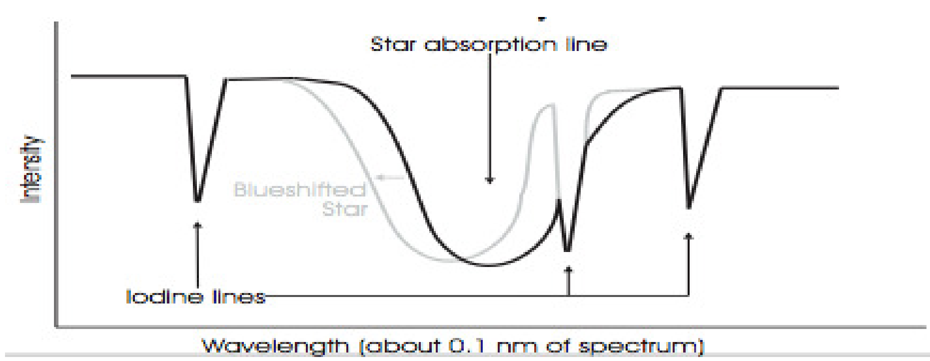
Fig. 1. This figure shows the motion through space of an unequal-mass binary system, with the center-of-mass shown traveling along a straight path.

Planets are very close to their parent stars in terms of angular distance from our earth-bound vantage point, and they are at least a million times fainter than their sun. We can readily see the star, however, and although its orbital motion is much less than that experienced by the planet, the instruments available to astronomers today are able to detect such motion.

Doppler Technique

Unless the orbital plane of a star-planet system is perfeclty perpendicular to our line-of-sight, some part of the orbital motion will be radial, that is, toward and away from earth. Radial motion causes a Doppler shift in the spectrum of the starlight coming toward us– a blueshift for motion toward us–and a redshift for motion away from us. The motions induced in the star over the orbital time of the planet are only about 100 meters per second for very large planets, and less than 1/2 meter per second for earth-like planets. It takes a high-resolution spectrograph plus many technical tricks to measure velocities so tiny.

The primary trick used by extrasolar planet researchers such as Geoff Marcy and Paul Butler is to filter the starlight through a transparent cell filled with iodine gas. The gas adds thousands of tiny little absorption lines on top of the spectrum of the star. The stars absorption lines are wider than those of the iodine because of the hot and turbulent conditions in the stars atmosphere. The trick is that the iodine always has velocity of zero, so that very precise Doppler measurements can be made of the stars absorption lines relative to the ultra-stable iodine lines (figure 2).



Using this technique, Marcy & Butler and others reach an astonishing 3 meters per second accuracy. The first sun-like star to have a confirmed planet is named 51 Pegasi, a star that can be found in any good quality star atlas just west of the great square of Pegasus. Some of the Marcy & Butler groups data from 1995 and 1996, taken with the Keck telescope, appears in the table below. The date is given in days (JD stands for Julian Day, a standard way of keeping time for celestial events). At each time listed, a Doppler observation was taken with results listed. A column for measurement uncertainty is given as well, even though we will not use this information here: it is always good scientific practice to compute and list the uncertainty in each measurement. For instance, 56 and 60 m/s are not statistically different from each other if the uncertainty is 5 m/s!

1. Discovering an extrosolar planet

Below is a table with actual published data from the first discovery of an extrasolar planet. It gives the host star's radial velocity as a function of time (negative velocities indicate the star is moving toward us).

Phased date	Date (JD-24500000)	Velocity (m/s)	Uncertainty (m/s)
1.62	21.62	56.4	4.5
1.71	21.71	66.8	6.4
	23.60	-35.1	5.1
0.44	24.64	-33.5	2.6
	24.82	-22.7	3.7
	27.65	-22.7	4.3
	28.61	-44.1	4.7
	28.66	-33.6	4.8
	29.61	25.1	4.3
	29.75	41.1	4.3
	30.60	61.3	5.6
	31.66	-2.5	5.0
	31.71	0.8	5.7
	31.75	-4.6	5.9
	32.69	-38.8	4.7
	33.61	2.7	4.4

- If a planet is perturbing its star, what trend do you expect to see if you plot velocity versus date? Draw a little sketch of what you expect over **one** orbital period.

- Make a graph of these obesrvations using excel, plotting dates along the bottom (x) axis and velocities along the vertical (y) axis. Make a drawing of your plot below:

- Discuss your graph. How is what you obtained different than your expectation? Does your graph say that there isnt a planet? Based on your graph at this point, can you put any upper or lower limits on the orbital period of a possible planet? (you should answer yes - explain your reasoning)

- Fill in the phased date column in table 1 in the following way: Let us assume, through a fit of inspiration, that the planet orbits in a period of 4.2 days (feel free to try other periods as well). We are going to wrap the dates in such a way that they repeat after 4.2 days. Assume our orbit starts at date = 20 days. Subtract 20 days from the first few dates and enter them in the phased date column. But if any subtraction exceeds 4.2 you have to subtract an additional 4.2 from the date. So after a while you will be subtracting 24.2. Then 28.4. Got it?

- Now plot velocity against phased date (again on the computer). Since 4.2 is the correct period for the planet, you should get something through which you can draw a sinusoidal curve (within the uncertainties). Sketch your plot below, drawing a curve through your points:

  Note that the period of 51 Pegs planet is surprisingly short. Mercury takes 88 days to get around the sun one time, 51 Pegs planet zips around in 4.2 days!

- Let us calculate the mass of the planet. The mass we will derive is for the case where we share the same plane as the orbiting planet. If we are seeing the system from a pole-on viewpoint then the motion we detect is only a fraction of the actual motion so the mass of the planet could be substantially larger than the number we are about to get. We get lucky in one way: 51 Peg is the same mass as the sun, so we can use Keplers 3rd law (without Newtons improvements) to find the semi-major axis of its orbit: $P^2 = a^3$ if the period is expressed in years and the semi-major axis is expressed in A.U. Convert P to years and compute a:

If we know how far the planet is from its star and its period, we know its circular velocity:

$$v_{planet} = \frac{distance}{time} = \frac{2\pi a}{P}$$

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- Compute v_{planet}:

The circular velocity of the star can be found from your graph:

$$v_* = \frac{1}{2}(v_{*,max} - v_{*,min})$$

- Compute v_*:

Since we are dealing with a center of mass problem, the masses of star and planet are in inverse proportion to their circular velocities: $m_{planet}/m_{star} = v_{star}/v_{planet}$. Convert all quantities to meters per second or kilograms. (1 A.U. = 1.49×10^{11} m, and the mass of the sun is 1.99×10^{30} kg)

- Now solve for the mass of the planet:

- For scale, convert your mass to Jupiter masses ($M_J = 1.90 \times 10^{27}$ kg) and to earth masses ($M_E = 5.97 \times 10^{24}$ kg):

- Can you think of complications that we did not consider in our analysis? What impresses you most about this planet?

Congratulations! You have discovered an extrasolar planet! You did so by noting the wobble of a star due to an orbiting planet.