ASTRO 1050
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.

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 Fig. 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 figure below. Most of the time, the planet is invisible to an observer.

Fig. 1.—: (Source: Unknown)

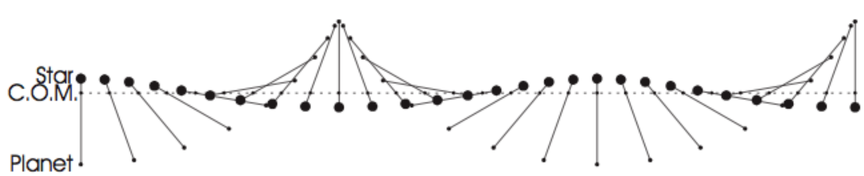


Fig. 1. This figure shows the motion through space of an unequal-mass binary system, with the center-of-mass shown traveling along a straight path.

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 parent star. 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 perfectly 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 (a.k.a. 1 mile per hour!). It takes a high-resolution spectrograph plus many technical tricks to measure velocities that are so tiny.

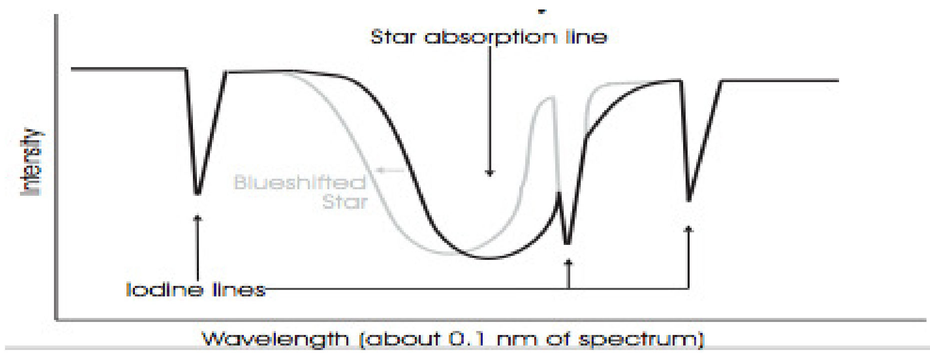
The primary trick used by extrasolar planet researchers is to filter the starlight through a transparent cell filled with iodine gas. The gas adds thousands of tiny little absorption lines on top of the spectrum of the star. The star's absorption lines are wider than those of the iodine because of the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

Using this technique, researchers reach an astonishing 3 meters per second precision. 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 data from that planet 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, 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 extrasolar 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).

Fig. 2.—: (Source: Unknown)



Data for 51 Peg

Phased date	Date (JD-2450000)	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 you plot velocity (y-axis) versus date (x-axis), what do you expect to see if a planet is tugging on its parent star as it orbits? Draw a little sketch of what you expect over **one** orbital period. Be sure to mark the start and end of the orbital period on your sketch!

Date/Time −− >

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

- Discuss your graph. **(a)** How is what you obtained different than your expectation? **(b)** Does your graph say that there isn't a planet? **(c)** 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) Meaning, what is the longest orbital period in your data and what is the shortest?

- 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. We are going to wrap the dates with 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.
  - 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 (y-axis, second column) against phased date (x-axis, first column) using Excel. 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 Peg's planet is surprisingly short. Mercury takes 88 days to orbit the Sun once, 51 Peg's 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 obtain. We get lucky in one way: 51 Peg is the same mass as the Sun, so we can use Kepler's 3$^{\text{rd}}$ law (without Newton's improvements) to find the semi-major axis of its orbit:

$$\mathrm{P}^2 = \mathrm{a}^3$$

where,
P = period in years (Recall, we know that 51 Peg has an orbit of 4.2 days.)
a = semi-major axis (or the "average distance of the planet's orbit") in A.U.

Convert P to years:

Then, compute a:

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

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

- Compute v_{planet}[1]:

[1] Remember your units!

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

$$\mathrm{v}_{star} = \frac{1}{2}(v_{star,max} - v_{star,min})$$

- Compute[2] v_{star}:

[2]Seriously, your units!

Since we are dealing with a center of mass problem, the masses of star[3] and planet are in inverse proportion to their **circular velocities**:

$$m_{planet}/m_{star} = v_{star}/v_{planet}.$$

1. Convert all quantities (v_{star}, v_{planet}, and m_{star}) to meters/second and kilograms.

   Conversions:
   1 A.U. = 1.49×10^{11} m
   Mass of the Sun is 1.99×10^{30} kg
   86400 seconds = 1 day

2. Now solve for the mass of the planet, m_{planet}:

[3]Remember that 51 Peg is about the same mass as the Sun!

3. To give a sense of 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):

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