Lab #5

## <u>Searching for Extrasolar Planets</u>

<u>Introduction</u>

Since the beginning of recorded history, humans have wondered whether we are alone in the Universe. Recently, Astronomers have begun to make significant progress toward answering this question. For the first time in history, we have detected planets around other stars ("extrasolar planets"). Surveys conducted by several teams of Astronomers have turned up evidence of planets around hundreds of other star systems.

Finding extrasolar planets hasn't been achieved in the past simply because we haven't had the technological know-how to do it. Even using current technology, the kinds of observations needed to reveal the tiny, telltale motions of stars with orbiting planets is almost impossible, requiring extremely high precision and long hours of painstaking research. To help us understand how this technique works, we will first look at a typical extrasolar planetary system (shown below).
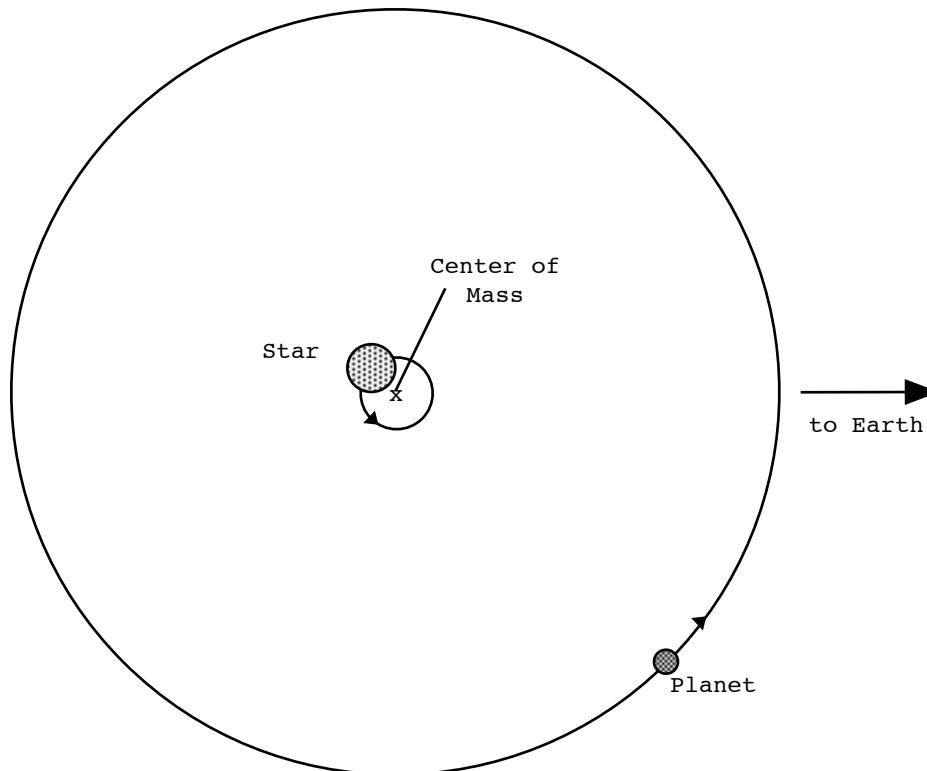
Although we cannot observe any of the properties of the orbiting planet directly, we can watch the central star "wobble" back and forth (toward and away from us) in response to the gravity of its companion planet and thus infer many properties about the orbiting planet. The central star and the orbiting planet revolve around a common center of mass. In our own solar system, the center of mass is offset a little bit from the center of our Sun because of the mass of Jupiter; the other planets have a much smaller effect on the location of the center of mass. Some alien astronomer analyzing the motions of our own Sun would see it appear to wobble in a tiny circle about the solar system's center of mass.

This wobbling motion is revealed by the Doppler shift of starlight. As a star moves radially back and forth relative to Earth, its light waves become stretched (redshifted) and compressed (blueshifted) periodically. From that cyclical shifting, astronomers can reconstruct the motion of the star. Then, using simple Physics (like Kepler's Law and Newton's Laws of Motion), we can compute the masses and orbital distances of orbiting companion planets. To detect planets around other stars with this technique requires amazingly precise instruments that can measure wavelength changes of 1 part in 100 million.

NASA has plans to launch a space-based telescope that uses the principles of interferometry to create a Planet Finder telescope. This mission will actually take photographs of Earth-like planets orbiting other stars. Even better, such a telescope could analyze the spectra of such planets to determine if they have atmospheres (and evidence of life).

First things first, though. Let's see how these planets are found to begin with before we start worrying about aliens. To determine the properties of planets around other stars, we must first make two important assumptions and perform two astronomical observations:

<u>Assumption #1</u>: The system is being observed edge-on

We must make this assumption first in order to apply the equations we'll use below. That's because we'll be using the Doppler shift of the star as the equivalent of the star's orbital velocity. If the system is not edge-on, then the Doppler shift will be smaller than the star's true orbital

velocity, and our final answer will be incorrect. We'll return
to this point later.

<u>Assumption #2</u>: The star that the planet is orbiting has the
     same mass as our Sun.

     One of the quantities we'll need to figure out the properties
of the orbiting planet is the mass of the central star. Most
survey teams limit their observational samples to Sun-like
stars, meaning stars that have all of the same properties (mass,
size, composition, temperature) as our own Sun, so this
assumption is a safe one to make. We're also assuming that all
planetary orbits are perfect circles, which is probably close to
the truth in most cases.

<u>Observation #1</u>: The Doppler shift of the star.

     We must first observe how the wavelengths of light from the
wobbling star shift to the blue (shorter wavelength) and to the
red (longer wavelength) of their rest wavelength. These shifts
are directly proportional to the star's radial velocity,
according to the Doppler shift equation:

$$\frac{\text{Change in wavelength}}{\text{Wavelength}} = \frac{\text{Radial velocity of star}}{\text{Speed of light}}$$

<u>Observation #2</u>: The Period of the orbit

     We must also observe how the star's Doppler shift varies over
time. Presumably, if we watch the star for a long enough time,
the pattern of Doppler shifting will repeat every time the star
makes an orbit around the center of mass point of the system.
This period will be the same as the period of the orbiting
planet!

Step 1
     On the data sheet included with this lab is a graph of radial
velocity vs time for three different stars, 47 Ursae Majoris (47
UMa), HD 40979, and 51 Pegasi (51 Peg). Remember, we have no
way of detecting the radial velocity of an orbiting planet
directly. Those orbiting planets (if they exist) are much too
faint to detect directly (i.e. with a photograph) with current
technology.

To find the orbital velocity of each star about the center of mass of its system, we need to measure the difference between the maximum and minimum shift values. That way, we're getting the shift on each side of the orbit. If we take the difference between these two shifts and divide by two, then we will have found the orbital velocity of the star.

For each star, determine the maximum and minimum values of the radial velocity, the difference between the two (divided by 2) and fill in these values on your worksheet (use two significant figures). We'll do the first calculation for 47 UMa together in class to help you get started.

Step 2
Next we need to determine the Period of the orbit. The period is just the time (in days) that it takes for the star to complete an orbital "cycle".

> **47 UMa:** You can actually see three entire cycles stretching from 1988 to about 1997.
>
> – Estimate to the nearest tenth of a year the times of the first and last minima.
>
> – Take the difference between the two and divide by 3 (since you are adding up 3 periods) to find the period of this star's orbital wobble.
>
> – Convert this time (in years) to seconds by multiplying by the conversion factor 3.2×10^7 seconds per year.
>
> – State your answer in scientific notation with two significant figures.
>
> **HD 40979:** For this star, you can see seven complete cycles. The x-axis measures time in years.
>
> – Estimate to the nearest tenth of a year the time of the first and last minima and write these values on your worksheet.
>
> – Take the difference between these two times and divided by 7 (since you are adding up 7 periods).

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– Finally, convert this time (in years) to seconds by
      multiplying by the same conversion factor used above.

  – State your answer in scientific notation with two
      significant figures.

  51 Peg – For this star, you can see seven complete cycles.
      Note the x-axis measures the time in days.

  – Estimate to the nearest tenth of a day the time of the
      first and last minima.

  – Take the difference between these two times and divide by
      seven to get the period (in days).

  – Finally, convert this time (in days) to seconds by
      multiplying by the conversion factor of 86,400 seconds
      per day.

  – State your answer in scientific notation with two
      significant figures.

Step 3

   Now that we've found the velocity of the star and the orbital
period of the star and planet, we have to do some calculations
to discover the mass and the orbital distance of the companion
planet. We will start with two equations that govern orbits:

$$v_{orbit} = \sqrt{\frac{GM}{r_{orbit}}}$$

v_{orbit} = orbital velocity of the planet
G = gravitational constant, 6.67×10^{-11}
M = mass of central star, 2.0×10^{30}
r_{orbit} = orbital distance from star to planet

$$2\pi r_{orbit} = v_{orbit} * Period$$

   The first equation is simply the equation of orbital velocity
that comes from the definition of an orbit: a path taken by an
object that balances centrifugal force with gravitational force.
The second equation is just a different way of writing "distance
= velocity * time".

   In this case it is, "Circumference of the orbit = orbital
velocity * time it takes to complete an orbit".

These two equations combine to create Kepler's 3rd Law of Planetary orbits, relating the orbital distance of a planet to its orbital period:

$$r^3_{orbit} = \frac{GM(Period)^2}{4\pi^2}$$

For each system, use the Period (in seconds) from step 2, and values for G and M given in the orbital velocity formula on the previous page, in order to calculate r_{orbit}. Write down the answer on your worksheet in scientific notation with two significant figures. Check your work with your partner or another group to be sure you have done this calculation correctly.

The Earth's orbital distance from the Sun is 1.0 Astronomical Units (or 1.0 AU), which is 1.5×10^{11} meters. Divide your answer for orbit by the conversion factor 1.5×10^{11} to determine the distance from the planet to its parent star in AU.

Step 4
Now let's determine each planet's orbital velocity and, from this, each planet's mass. Finding the orbital velocity is easy...just solve the second orbit equation like this:

$$v_{planet} = \frac{2\pi r_{orbit}}{Period}$$

For each system, determine the orbital velocity of the companion planet in meters/sec. In the equation above, be sure to use r_{orbit} in meters and P in seconds.

Finally, Newton's Laws tell us that there is a very simple (approximate) relationship between the masses of two orbiting bodies and the velocities of two orbiting bodies:

$$M_{planet} = \frac{v_{star}}{v_{planet}} M_{star}$$

from step 1 → v_{star}

use 1000 here → M_{star}

from step 4 → v_{planet}

Assumption #2 tells us that we can assume that the mass of the parent star is the same as the mass of our own Sun, which we know to be **1000 Jupiter-masses**. Using this information and the equation above for each system, solve for the mass of the orbiting planet in Jupiter-masses. Answer with two significant figures.

Step 5 – Errors

The main source of error in this experiment is assumption #1 (that we are observing the systems edge-on). Remember that if our assumption is wrong then the true stellar velocity will be larger than the value we used in this experiment. Fill in the following statement: "If our edge-on assumption is wrong, then the true mass of the planet will be (larger/smaller) than the mass we determined in this experiment." Explain your reasoning. A diagram may help with this part.

Finally, given the planet masses below calculated in published papers by the research teams, using the edge-on assumption (shown below), calculate your percent error for each case.

47 UMa: 2.4 M_{Jup} // HD 40979: 3.3 M_{Jup} // 51 Peg: .47M_{Jup}

Essay

In the first paragraph of your essay, use one sentence each to state your results (planetary mass and orbital distance in AU) for each of the three planetary systems. In the second paragraph, discuss whether, if we were to visit these solar systems, they would look anything like our own. Finally, discuss the implications of these discoveries on our own "solar nebula" theory of solar system formation that says all Jupiter-sized planets (and larger) should be formed in the outer reaches of the solar system.
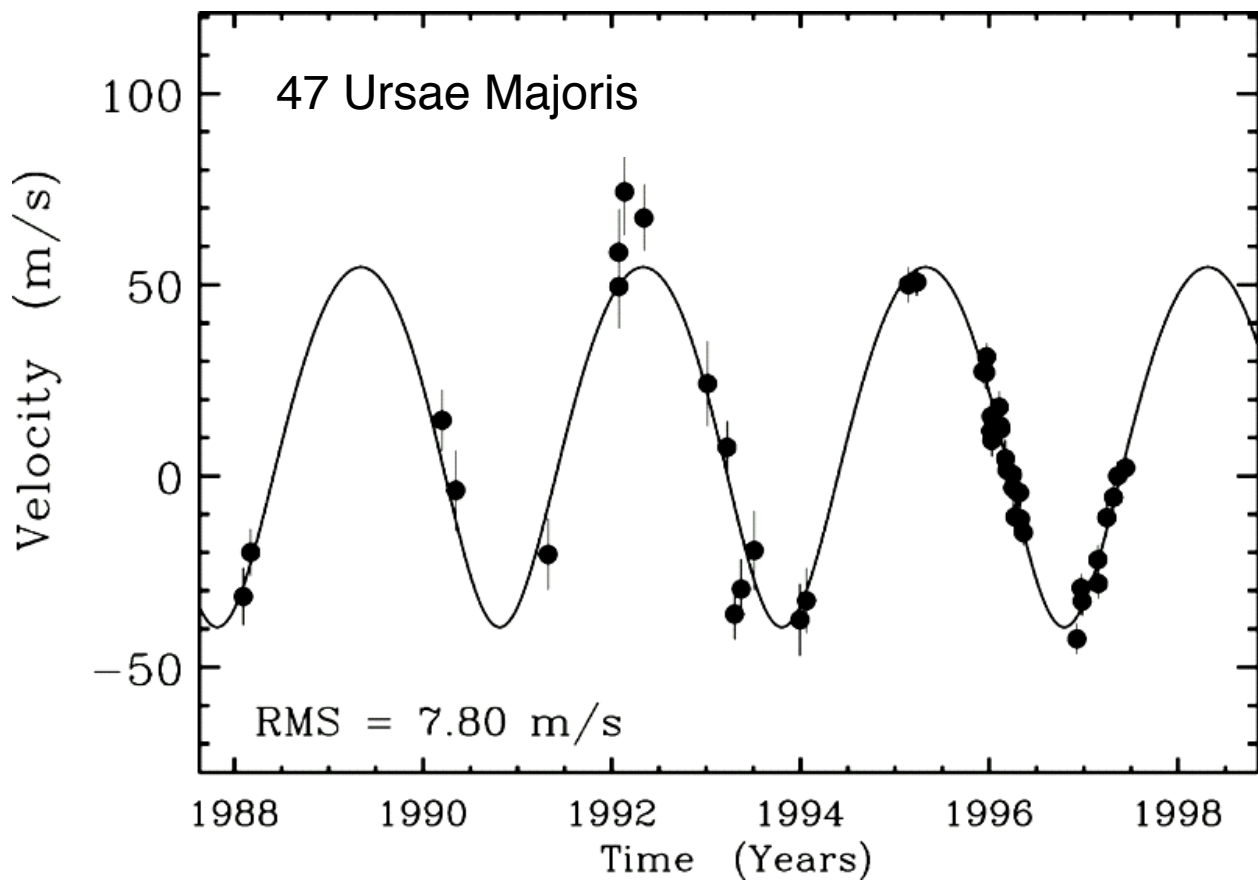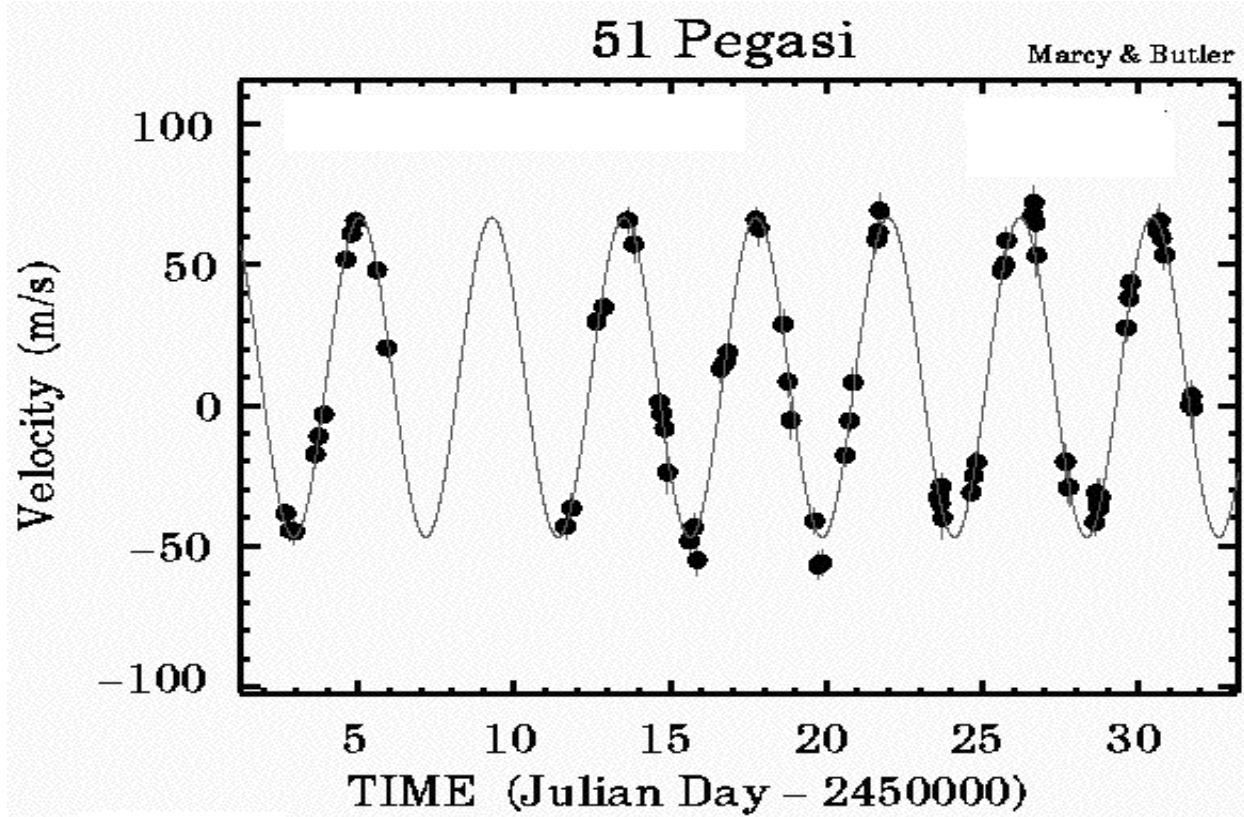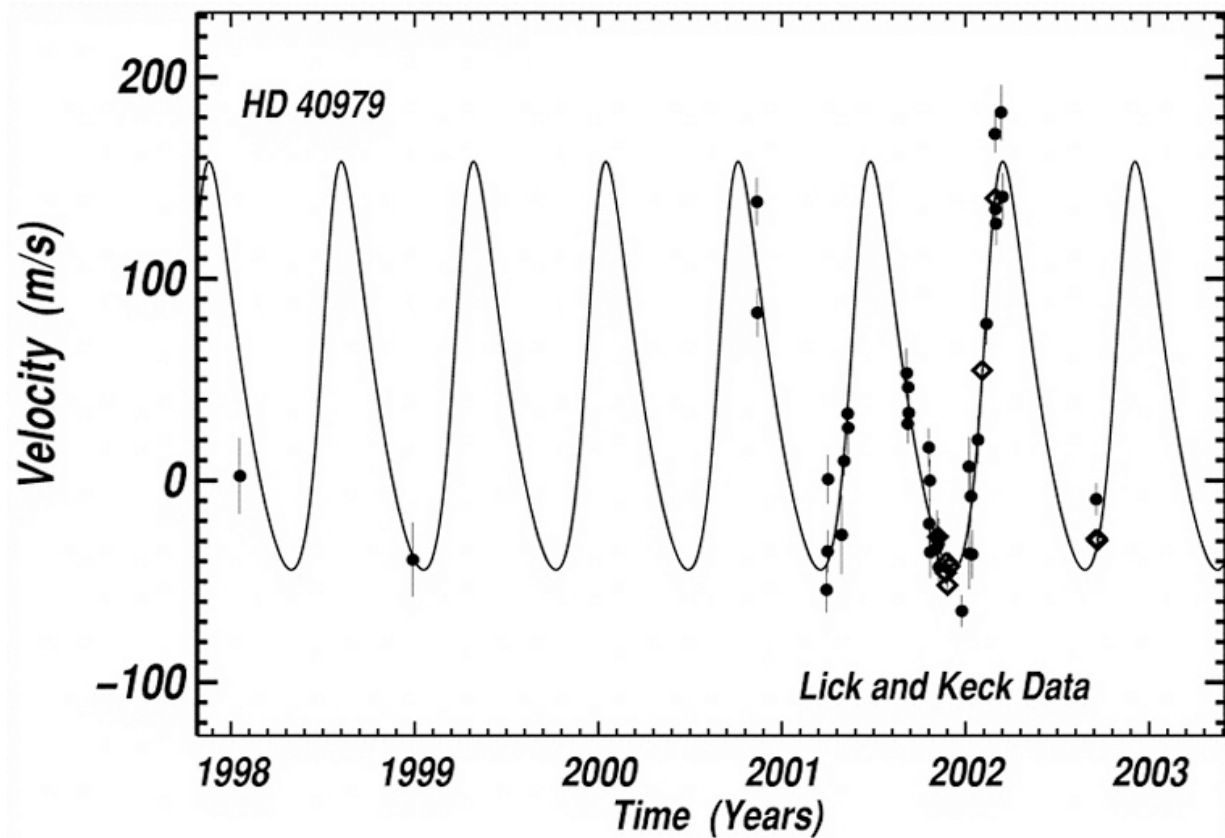
Sources

47 UMa: www.public.iastate.edu/~astro.505/firstwk.html

HD 40979: www.markelowitz.com/exobiology.htm

51 Peg: www.astro.lsa.umich.edu/undergrad/labs/
          extrasolar_planets/pn_51Peg_vt.gif

Data

HD 40979

Lick and Keck Data

51 Pegasi

Marcy & Butler

Lab #5 Worksheet

Name:
Home TA:

Step 1
47 UMa:

    Maximum velocity: _____ m/s.

    Minimum velocity: _____ m/s.

    (Max velocity – Min velocity)/2 = v_{star} = _____ m/s.

HD 40979:

    Maximum velocity: _____ m/s.

    Minimum velocity: _____ m/s.

    (Max velocity – Min velocity)/2 = v_{star} = _____ m/s.

51 Peg:

    Maximum velocity: _____ m/s.

    Minimum velocity: _____ m/s.

    (Max velocity – Min velocity)/2 = v_{star} = _____ m/s.

Step 2
47 UMa:

    First minimum: _____   Last minimum: _____

    (Last time – first time)/3 = P = _____ years.

    P * 3.2 x 10^7 = _____ sec. (**Use this in step 4.**)

HD 40979:

    First minimum: _____   Last minimum: _____

    (Last time – first time)/7 = P = _____ years.

    P * 3.2 x 10^7 = _____ seconds. (**Use this in step 4.**)

51 Peg:
    First minimum: _____   Last minimum: _____

    (Last time - first time)/7 = P = _____ days.

    P * 86,400 = _____ seconds.   (**Use this in step 4.**)

Step 3
47 Uma:
    r^3_{planet} = _____ m^3. r_{planet} = _____ m.
                                      ^^^ **Use this in step 4!** ^^^
    r_{planet} / 1.5 x 10^{11} = _____ AU.

HD 40979:
    r^3_{planet} = _____ m^3. r_{planet} = _____ m.
                                      ^^^ **Use this in step 4!** ^^^
    r_{planet} / 1.5 x 10^{11} = _____ AU.

51 Peg:
    r^3_{planet} = _____ m^3. r_{planet} = _____ m.
                                      ^^^ **Use this in step 4!** ^^^
    r_{planet} / 1.5 x 10^{11} = _____ AU.

Step 4
47 Uma:
    v_{planet} = _____ m/s. M_{planet} = _____ M_{Jup}

HD 40979:
    v_{planet} = _____ m/s. M_{planet} = _____ M_{Jup}

51 Peg:
    v_{planet} = _____ m/s. M_{planet} = _____ M_{Jup}

Step 5

    If our edge-on assumption is wrong, the true planet masses

will be _____ than the masses we just calculated.

Briefly explain your answer in the space below.

% Error for 47 UMa planet: _____%

% Error for HD 40979 planet: _____%

% Error for 51 Peg planet: _____%

Essay (on reverse side)