EXOPLANETS

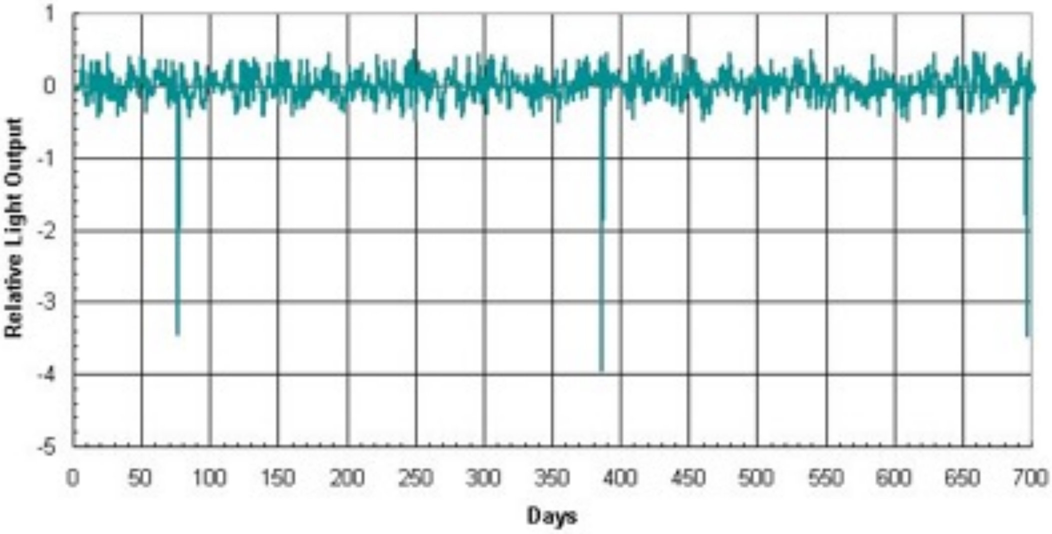
Introduction

Since the early 1990's more than 1000 extrasolar planets or exoplanets have been discovered. Most of these planets, that orbit stars other than our Sun, are large gaseous planets with masses comparable to Jupiter's mass.

Astronomers can employ the same three primary methods used in studying binary star systems to detect exoplanets, but only by using much higher precision measurements.

- **Photometry** - the measurement and analysis of the amount of light coming from a celestial object. Periodic drops in light intensity may indicate the presence of an unseen planet when it obstructs some of the light output from the star as it transits the disk of the star.
- **Astrometry** - the measurement and analysis of the position of a star against the background of surrounding stars. A star demonstrating a regular oscillation in position may have an unseen planet orbiting it causing a "wobble" around the center of mass of the star-planet system.
- **Spectroscopy** - the measurement and analysis of the spectrum of a star. As the star and planet orbit about their mutual center of mass a very slight shift in position of the star may be detected through the periodic Doppler shifting in the position of the spectral lines.

The photometry data provided simulates that expected from the Kepler mission in its search for potentially habitable exoplanets. When a planet passes in front of the star (making a transit across the star), the total light output drops accordingly, causing the larger observed dips in the graph.



The graph plots the un-calibrated signal minus the average signal from the instrument.

In the following exercise data are presented for two stars of spectral types **F5V** and **M0V**.

I. Calculating Orbital Information from the Observational Data

A. Period

Determine the average time between transits of the planet across the star's disk.

B. Orbit

Newton's form of Kepler's third law of planetary motion relates the orbital period of a planet in our solar system and the mass of the Sun to the planet's average distance from the Sun:

$$p^2 M = a^3$$

where

- **p** is the orbital period of the planet (*years*)
- **M** is the mass of the star (*solar masses*)
- **a** is the average distance of the planet from the star (*Astronomical Units*)

If the star is a main sequence dwarf then its mass can be estimated from its spectral type by using Table 1.

Table 1

Spectral Type	**05**	**B0**	**B5**	**A0**	**A5**	**F0**	**F5**	**G0**	**G5**	**K0**	**K5**	**M0**	**M5**
Stellar Mass	40	17	7.0	3.5	2.2	1.8	1.4	1.07	0.93	0.81	0.69	0.48	0.22
Radius (sol.rad.)	17.8	7.59	3.98	2.63	1.78	1.35	1.20	1.05	0.93	0.85	0.74	0.63	0.32
Temp. (K)	35000	21000	13500	9700	8100	7200	6500	6000	5400	4700	4000	3300	2600

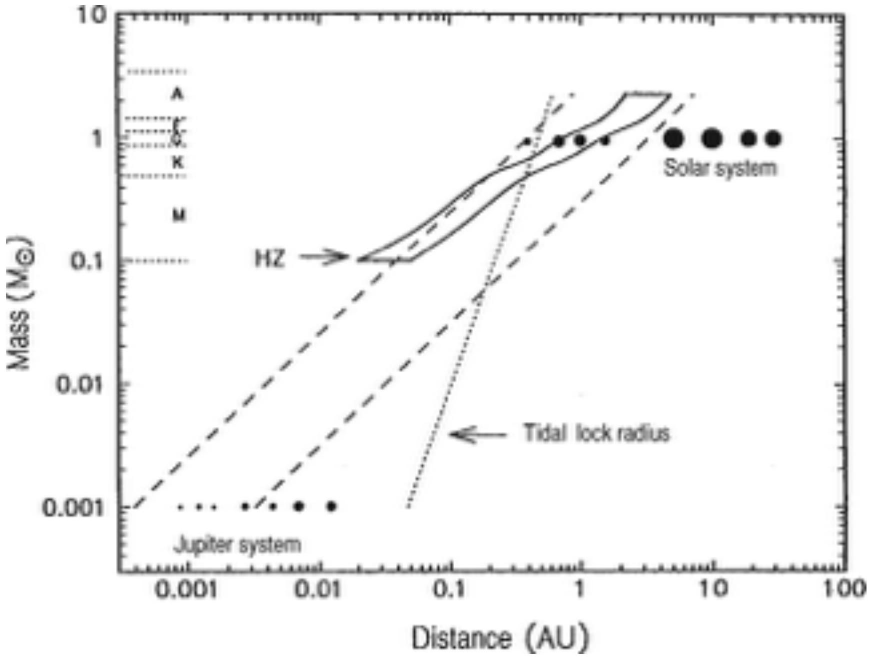
(Note: 1 AU = 215 solar radii.)

II. Is This Planet Potentially Habitable?

A plot of potentially habitable planets is found in Figure 1, taken from the paper by Kasting, Whitmire and Reynolds in *Icarus*, **101**, 108-128 (1993).

The mass of the star in solar masses is plotted against the orbital distance of the exoplanet. Note that the stars of different spectral types are also indicated. The dotted lines show the location of the zero subdivision of each spectral type, thus F5, for example, is between F0 and G0. The approximate size and position of the planets of our solar system are shown along the horizontal line corresponding to a star of one solar mass. [Source: Kasting, et al (1993).]

Figure 1



Indicate and label where the exoplanets would appear on this graph. (*Note that both the horizontal and vertical axes are logarithmic.*)

III. Surface Temperature

As a reasonable first approximation, the surface temperature of a planet can be related to the planet's distance from the parent star and how large and how hot the parent star is.

$$\mathbf{T_p = (R_{star} / 2\, a_{exoplanet})^{1/2}\, T_{star}}$$

where

- $\mathbf{T_p}$ is the average surface temperature of the planet (*Kelvins*)
- $\mathbf{R_{star}}$ is the radius of the parent star (*AU*)
- $\mathbf{a_{exoplanet}}$ is the semi-major axis of the planet's orbit about the star (*AU*)
- $\mathbf{T_{star}}$ is the surface temperature of the parent star (*Kelvins*)

IV. Size

A careful calibration and analysis of the original photometric data will yield the size of the exoplanet. Since all planets are large enough for gravity to pull them into a spherical shape, a calculation of the radius of the exoplanet gives a measure of its size.

The ratio of the light being blocked by the transit of the exoplanet to the total light usually reaching the photometer is equal to ratio of the cross-sectional areas of the exoplanet and the parent star. Since:

$$\mathbf{Area} = \pi * r^2$$

the percentage drop Δ in light from the star as the exoplanet transits the star is simply equal to the ratio of the squares of the radii of the exoplanet and the star.

$$\Delta = R^2_{exoplanet} / R^2_{star} \times 100\%$$

The radii of stars of different spectral types is given in Table 1.
(*Note: 1 solar radius = 109 Earth radii.*)

V. Mass

The mass of the exoplanet can be determined from an estimate of its density.

A. Model 1: Density as a function of planetary size

The average density ρ of an object is the mass per unit volume.
Since a planet is basically a sphere, its volume is:

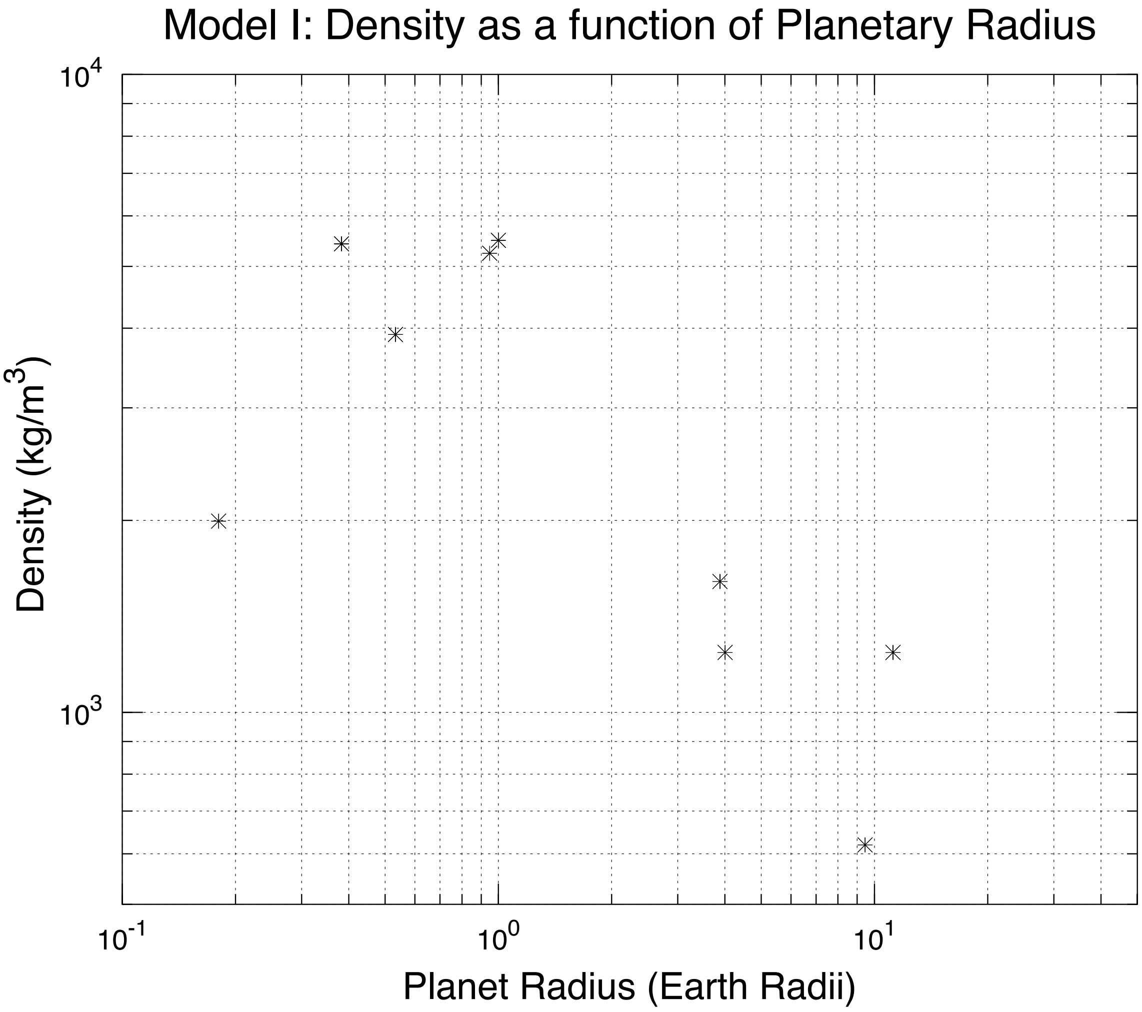
$$V = (4/3)\, \pi\, R^3$$

The mass of the exoplanet, given its density and radius is:

$$M_{exoplanet} = \rho * (4/3) * \pi\, R^3_{exoplanet}$$

A log-log plot of the densities and radii of the planets in the solar system is shown in Figure 2.

Figure 2



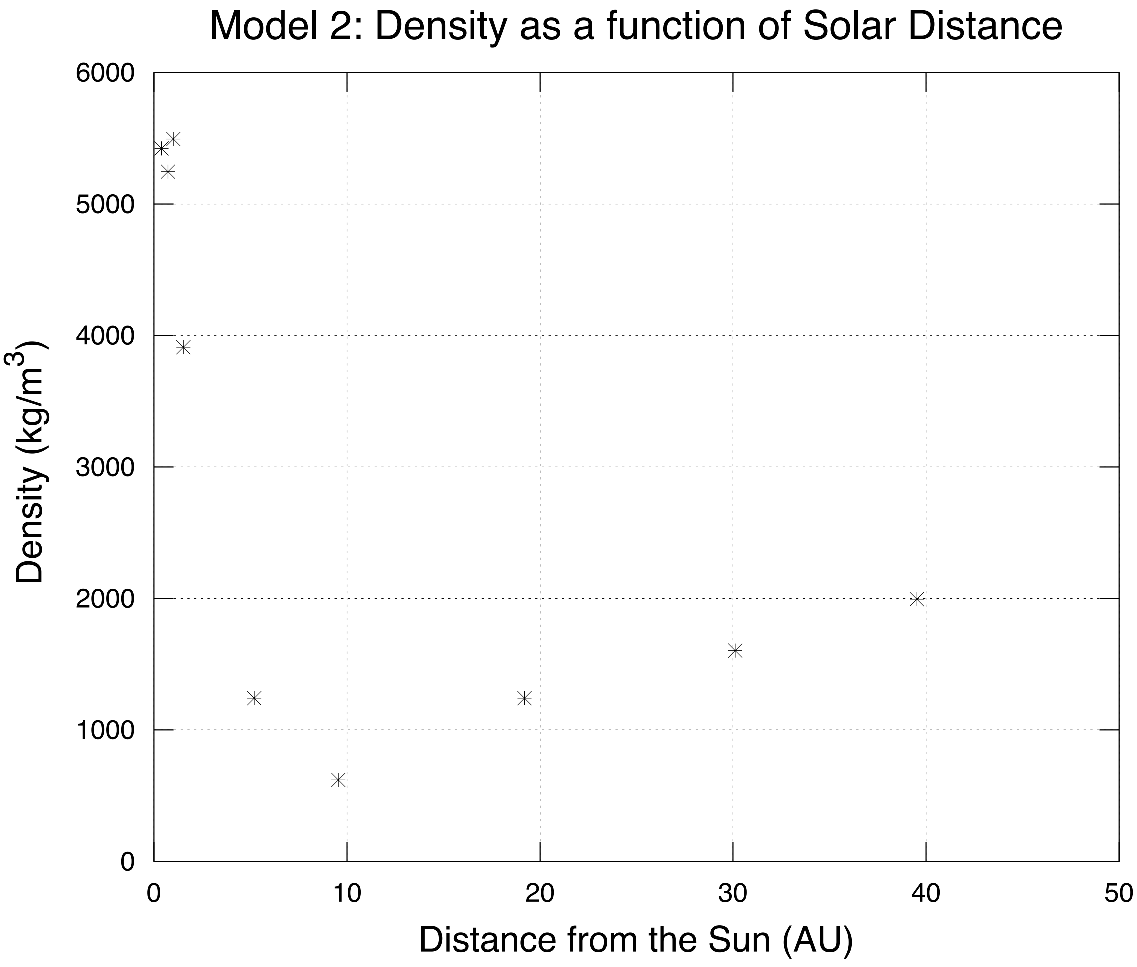
(Data for Earth: ρ *= 5500 kg/m*^{3}*,* ***M*** *= 5.98 X* 10^{24}*kg,* ***R*** *= 6.378 X* 10^6*m)*

Draw a line through the data points indicating an approximate best fit. Use the density value determined from this figure to calculate the mass of the exoplanet.

B. Model 2: Density as a function of planetary distance

A plot of the densities of the planets in our solar system with the average distance they are from the Sun is shown in the following.

Figure 3



Once again draw a line through the data points indicating an approximate best fit. Locate the semi-major axis of the exoplanet on the graph and read its associated density from the curve. Use this density value to once again determine the mass of the exoplanet.

$$\mathbf{M_{exoplanet} = \rho * (4/3) * \pi\, R^3_{exoplanet}}$$

VI. Surface Gravity

One of the important parameters for determining the size of structures possible on the surface of the exoplanet is the surface gravity.

$$\mathbf{g = G * M_{exoplanet} / R^2_{exoplanet} \qquad (G = 6.674 \times 10^{-11}\ Nm^2/kg^2)}$$

VII. Probability of Finding the Exoplanet

Even if a star has an orbiting planet, only in a very small percentage of cases will that planet make a transit across the disk of the star as seen from Earth's perspective.

The probability for a planet with a circular orbit is given by:

$$\textbf{probability (\%)} = (R_{\text{star}} / a_{\text{exoplanet}}) * 100\%$$

where

- R_{star} is the radius of the parent star in AU. (215 solar radii = 1 AU.)
- $a_{\text{exoplanet}}$ is the semi-major axis of the planet's orbit about the star, in AU

Questions:

Table 2

PHENOMENON	**TEMPERATURE**
gold melts	1336 K
Venus surface	730 K
lead melts	600 K
water boils	373 K
Earth (average)	***290 K***
water freezes	273 K
Mars surface	180-270 K
oxygen liquifies	90 K
absolute zero	0 K

1. Suggest several reasons why you might observe no significant dips in the signal.

2. Some suggested basic criteria for habitable planets are:
    - liquid water on or near its its surface.
    - hard crusty surfaces

    Do your exoplanets satisfy these criteria? Explain.

3. What assumptions are we making when we say that the percentage drop in light from the star as the exoplanet transits the star is simply equal to the ratio of the squares of the radii of the exoplanet and the star?

4. What factors determine the surface temperature of the planet?

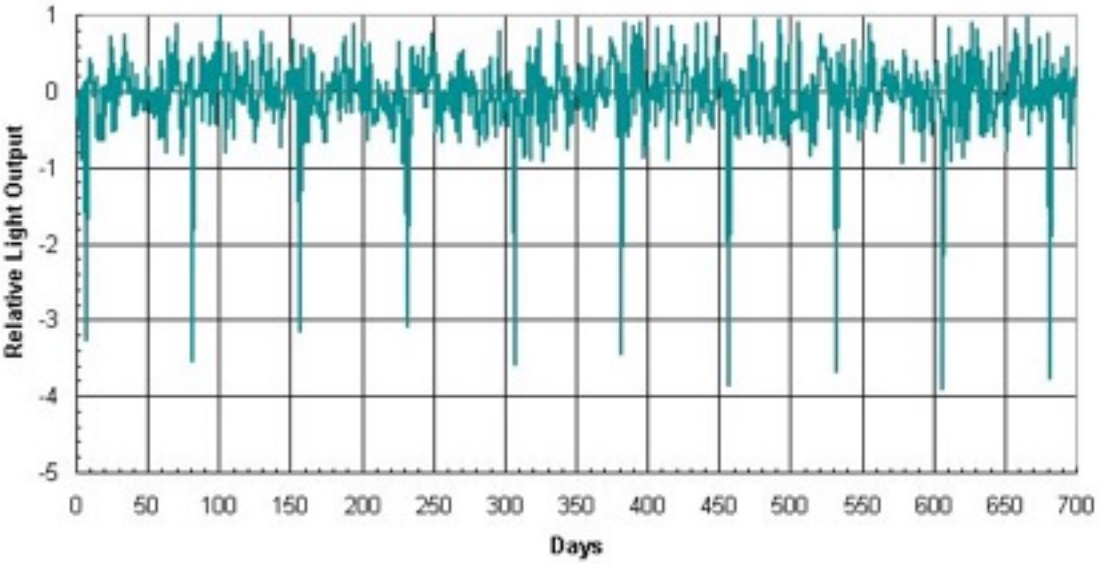
5. Table 2 indicates the temperature at which certain phenomena occur. Where do your planets fit in the table?

6. The models used to estimate the density of a planet are very simplistic. What should a more complete model for the density of a planet include at the very least?

7. The height of structures that can be built on the surface of a planet is determined by the surface gravity and the material from which it is built. The highest mountain on Earth from base to peak is the shield volcano Mauna Kea in Hawaii which rises 10 km from the ocean floor and is 120 across at its widest point, the highest mountain on Mars is also a shield volcano, Olympus Mons which rises 22km above the surrounding plain near the Tharsis plateau and is 700km at its base. What size similar structures are possible on your exoplanets?

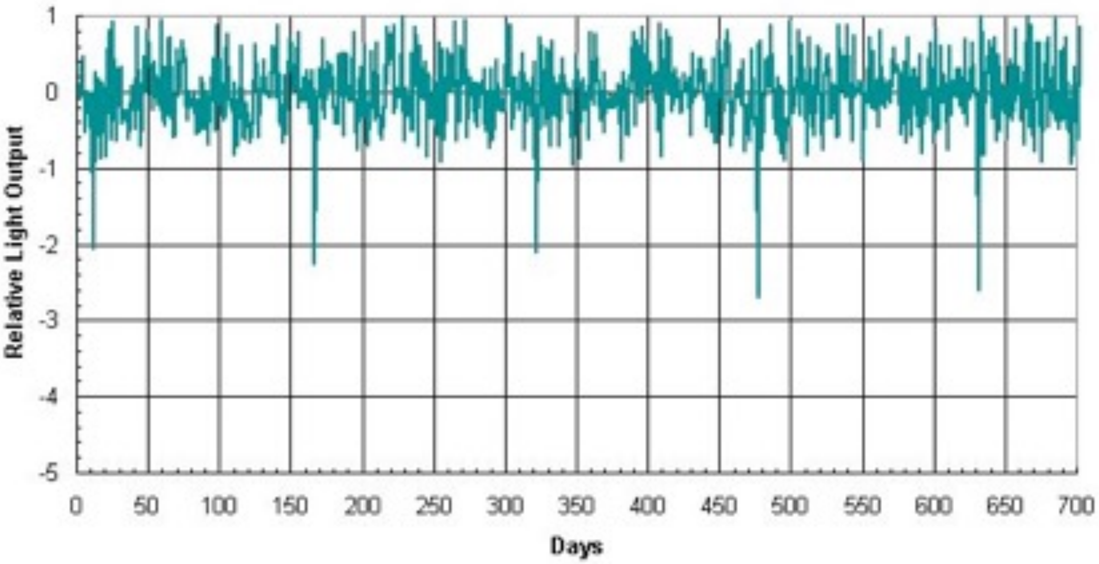
Adapted from: Finding Exoplanets: Using Observations of Transits (a simulation)
Simulation Authors: Richard L. Bowman (Bridgewater College) and David Koch (Kepler Mission)

Star number 1



Summary		
A. The Parent Star		Δ = 0.565%
1	Spectral Type:	**F5 V**
2	Apparent Magnitude:	**11**
B. The Exoplanet		
1	Orbital Period:	
2	Semi-major Axis of the Orbit:	
3	Habitable Zone Position:	
4	Surface Temperature:	
5	Radius:	
6	Mass (model 1):	
	(model 2):	
7	Surface Gravity	
8	Probability of Discovery:	

Star Number 2



Summary		
A. The Parent Star		Δ = 0.012%
1	Spectral Type:	**M0 V**
2	Apparent Magnitude:	**15.6**
B. The Exoplanet		
1	Orbital Period:	
2	Semi-major Axis of the Orbit:	
3	Habitable Zone Position:	
4	Surface Temperature:	
5	Radius:	
6	Mass (model 1):	
	(model 2):	
7	Surface Gravity	
8	Probability of Discovery:	