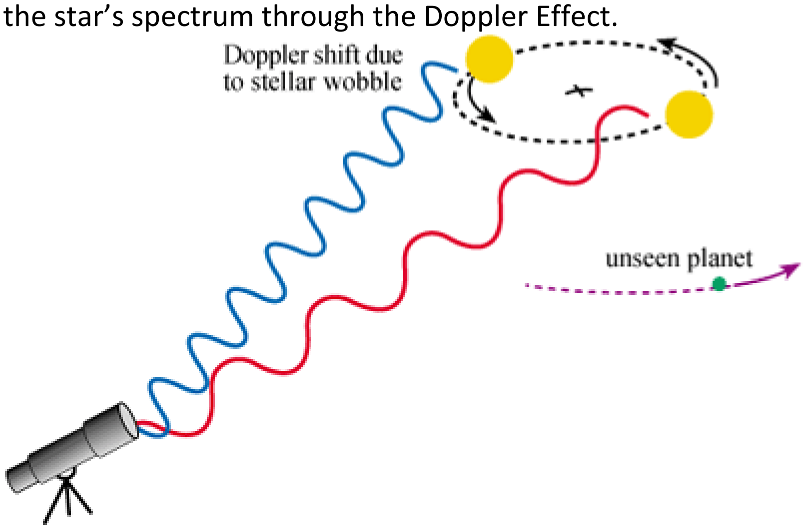
Lab 5: Searching for Extra-Solar Planets

Until 1991, astronomers only knew about planets orbiting our sun. Though other planetary systems were suspected to exist, none had been found. Now, 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 November 2019, over 4,000 extra-solar planets have been found in at least 2,500 planetary systems. Initially, most of these planets were Jupiter-sized and larger, but as observational search methods improved, astronomers began finding planets of smaller sizes. With the launch of *Kepler* in 2009, astronomers began to find Earth-like planets with the transit method. Although *Kepler* died in October 2018, a new space telescope called *TESS* will continue monitoring stars for dips in brightness.

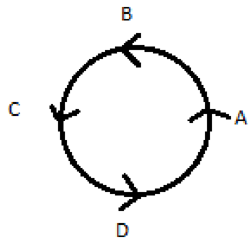
Part I: The Radial Velocity, or Doppler Wobble Method

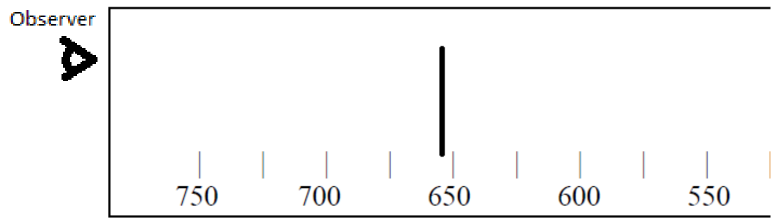
Before *Kepler*, more than 90% of the known extra-solar planet candidates have been discovered through the radial velocity, or Doppler wobble method. As more exoplanets were detected with transiting surveys, this percentage dropped to about 20%, with 778 confirmed planets discovered with the radial velocity 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).

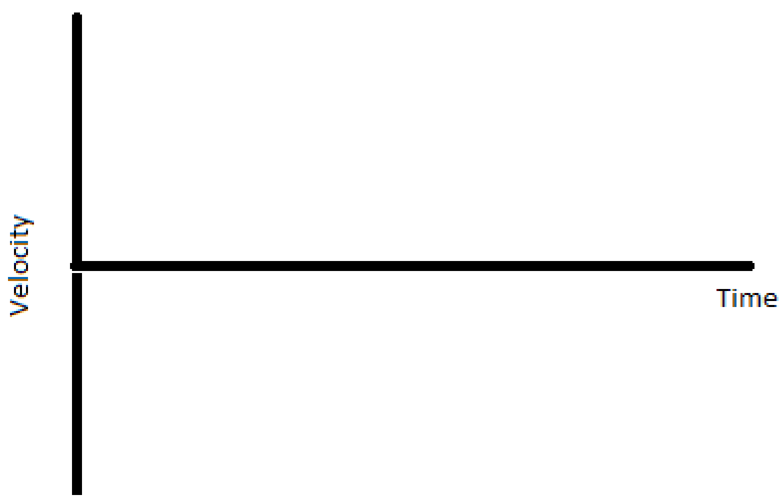
1. Below (left) is a sketch of a star at different points in a circular orbit caused by an unseen planet. On the right is the Balmer absorption line (656 nm) for an object at rest. Add to the spectrum the lines that would be seen by the observer at each of the four points in the star's orbit. Be sure to label the lines to correspond to the points on the left. Assume the star's velocity (and corresponding wavelength shift) is large.





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.

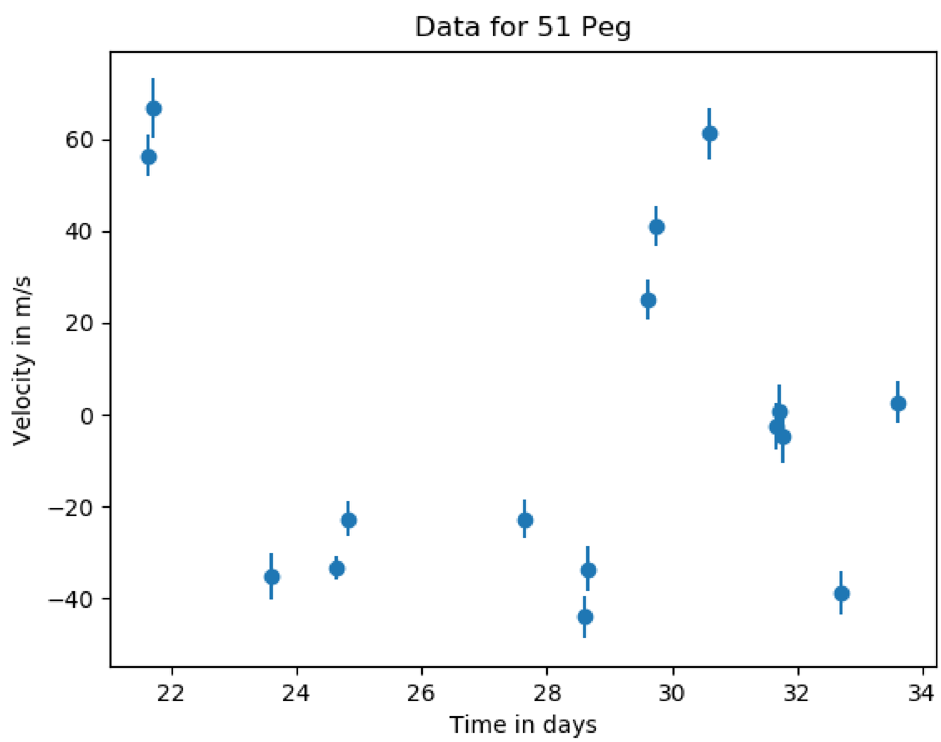


3. Once we've collected data for 51 Pegasus from the telescope, compiled in Table 1 below, the first thing to do is look at it by plotting the date on the x-axis and the velocities on the y-axis.

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:

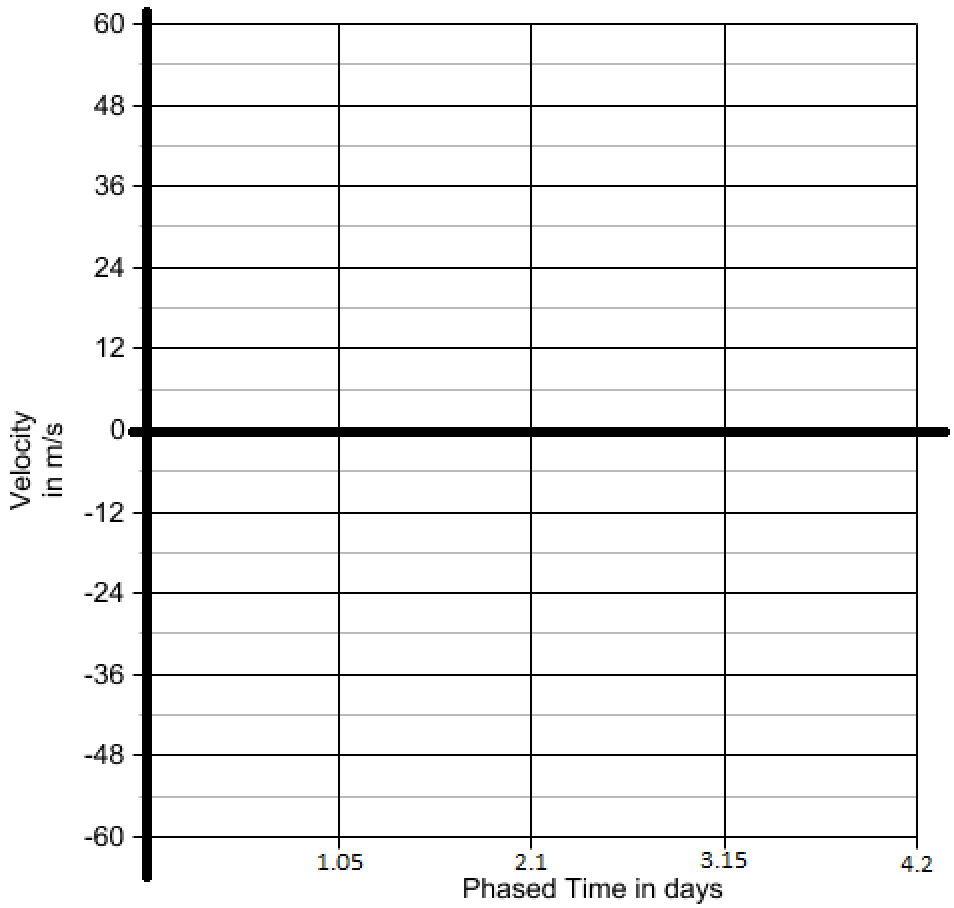


4. Describe this graph. Is it different from your expectations? Why?

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 (88 days).

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 3rd 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:

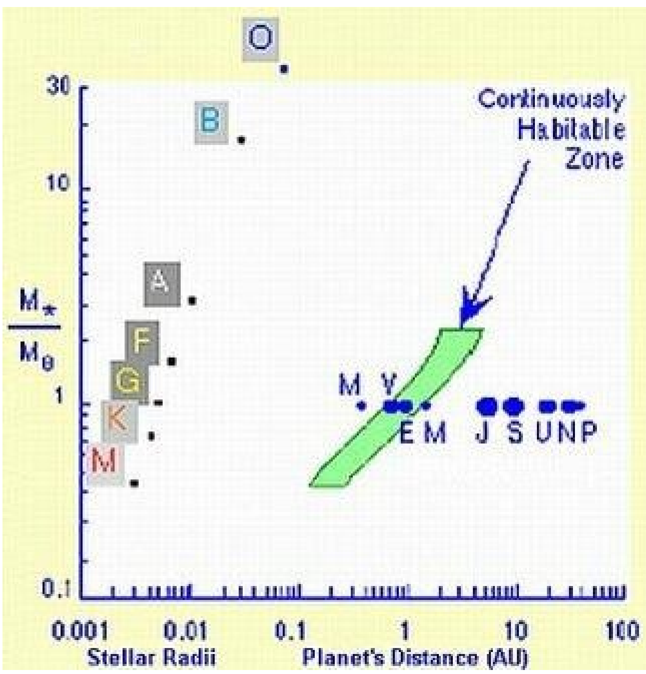
$M_{planet}/M_{star}=v_{star}/v_{planet}$

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=1.90x10^{27} kg) *and* to Earth masses (M_E=5.97x10^{24} kg)

7. Indicate on the plot below where your planet falls. (51 Peg has about the same mass as the sun.)



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). 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.

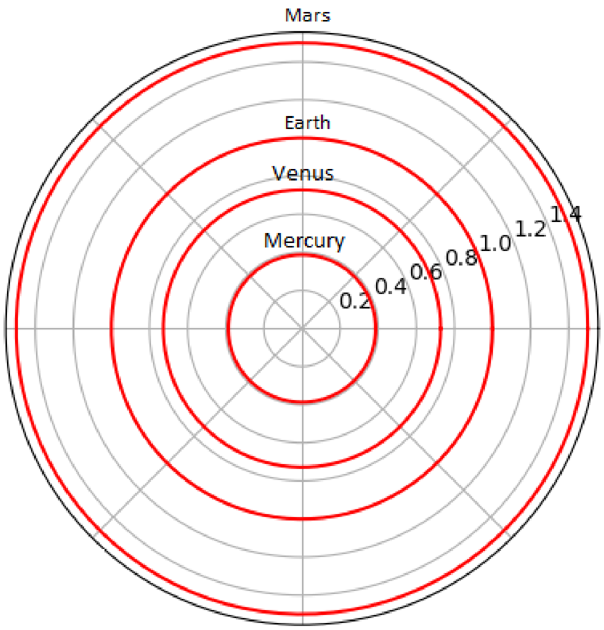
The habitable zone is defined by where one would expect to find liquid water in that solar system.

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

b. If not, what condition(s) make this planet uninhabitable?

9a. The planet around 51 Peg is thought to have a mass of 0.468 x M_{Jup}. Calculate the percent errors in your measured masses of the planet.
Note that percent error = (|your value – true value|/true value)*100.

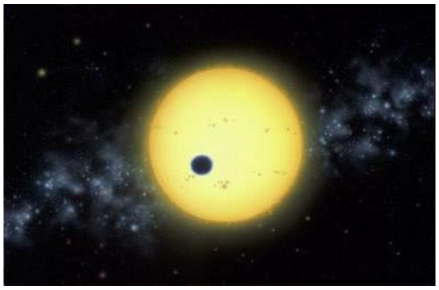
9b. On the following diagram, draw the orbit of the planet if it were in our solar system. The numerical labels indicate distance in AU, and apply to the grey circle *interior* to the label.



10. Could you detect Earth-like planets around stars like the Sun and 51 Peg using the Doppler method? The minimum detectable v_{star} is 3 m/s. (Hint: solve for the velocity of a solar-mass star being orbited by a planet with the same mass, period, and semimajor axis as Earth)

Part II: The Transit Method

Exercise A



Caption: credit: Lynett Cook

In the transit method, a star is monitored in the hopes of catching a dip in its brightness as a planet moves across its face. The *Kepler* and *TESS (*Transiting Exoplanet Survey Satellite) space telescopes were designed to monitor many stars over the course of multiple years.

As of November 2019, the *Kepler* mission detected 2345 confirmed exoplanets with the transit method, with more to come as the data is fully analyzed. *TESS* has detected 29 confirmed exoplanets, with many candidates that still need to be confirmed and more data coming in every day.

For this section, we will generate real data.

1. Sketch how the star's light would appear before, during and after the transit (e.g. you can put Star Brightness on the y-axis and time on the x-axis).

2. Examine a transit in a darkened room.

a Measure the light intensity before the transit and during the transit. Use planets of two different sizes and estimate the size of each from your light intensity measurements using the equations below:

Fractional light drop = [(intensity before) – (intensity during)] / (intensity before)

Fractional light drop = $(\text{exoplanet radius})^2/(\text{star radius})^2$

Measured star's radius:	

Intensity Before Transit	Intensity During Transit	Fractional light drop	Calculated size of exoplanet radius

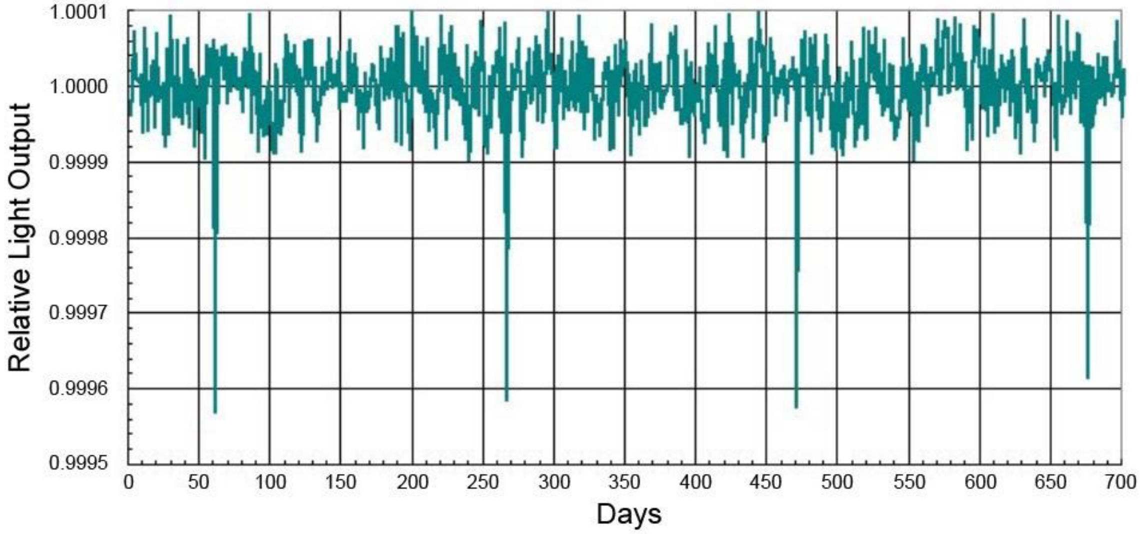
3. Measure the actual size of your exoplanet with a ruler. Compare your estimate of the planet's size with the actual size by calculating the percent difference: % difference = |observed size – true size|/true size * 100.

Measured size of exoplanet radius	Calculated size of exoplanet radius (from above)	Percent Difference

4. Comment on the agreement between your observed and measured values for your two planets.

Exercise B

For this section, we will use the simulated data below.



Caption: 700 days of observations of a star with spectral type K0.

1. Determine the period of the planet that appears to be orbiting this star. Explain how you got this answer.

2. Use Newton's modification of Kepler's third law, $P^2 M_{star} = a^3$ (where the Period, P, is in years, the mass of the star, M_{star}, is in solar masses and the semi-major axis, a, is in A.U.) to estimate the semi-major axis of the planet's orbit around its parent star. Note: you will need the mass of the K0 star, from the appendix.

3. Does this planet fall within its parent star's continuously habitable zone? (Hint: Use the figure from page 7.)

4. The size of an exoplanet in the transit method can be determined from the amount of light the planet blocks. The ratio of the light being blocked by the transit of the exoplanet to the total light usually reaching the telescope is equal to the ratio of the cross-sectional areas of the exoplanet and the parent star.

From the simulated data, measure the fractional light drop. Explain how you did this.

Since (area of a circle) = π radius^2, the fractional (or 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. (See the appendix for the star's radius.)

Fractional light drop = (exoplanet radius)^2/(star radius)^2

Use this to estimate the size of the exoplanet in Earth radii.
Hint: Use the fact that 1 solar radius = 109 Earth radii, or simply convert all your sizes to meters and convert to Earth radii at the end.

5a. 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 of detecting an exoplanet with a circular orbit is given by the ratio of the star's radius to the semimajor axis of the planet's orbit:
probabililty (%) = $(R_{star}/a)*100\%$

What is the probability of detecting this exoplanet?
Hint: Use the fact that 1 A.U. = 215 R_{sun}, or convert all your distances to meters.

5b. How can astronomers overcome the low probability of detecting planets using the transit method?

6. Discuss the strengths and weaknesses of the Doppler and transit methods for finding planets around other stars.

Appendix

I. Properties for stars on the main sequence of the H-R diagram.

Spectral Type	05	B0	B5	A0	A5	F0	F5	G0	G5	K0	K5	M0	M5
Radius (R_{sun})	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
Temperature (K)	35000	21000	13500	9700	8100	7200	6500	6000	5400	4700	4000	3300	2600
Stellar Mass (M_{sun})	40	17	7.0	3.5	2.2	1.8	1.4	1.07	0.93	0.81	0.69	0.48	0.22

II. Data for our solar system

Planet	Semi-major axis, a (AU)	Period, P (year)	Average orbital velocity (km/s)
Mercury	0.387	0.241	47.89
Venus	0.723	0.615	35.03
Earth	1.000	1.000	29.79
Mars	1.524	1.881	24.13
Jupiter	5.203	11.867	13.06
Saturn	9.539	29.461	9.64
Uranus	19.18	84.013	6.81
Neptune	30.06	164.793	5.43
Pluto	39.44	247.7	4.74

III. Miscellaneous Data

$R_{sun} = 6.96 \times 10^{8}$ m

$R_{earth} = 6.378 \times 10^{6}$ m

1 AU = 1.5×10^{11} m

$M_{SUN} = 1.98 \times 10^{30}$ kg

Bibliography

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https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html