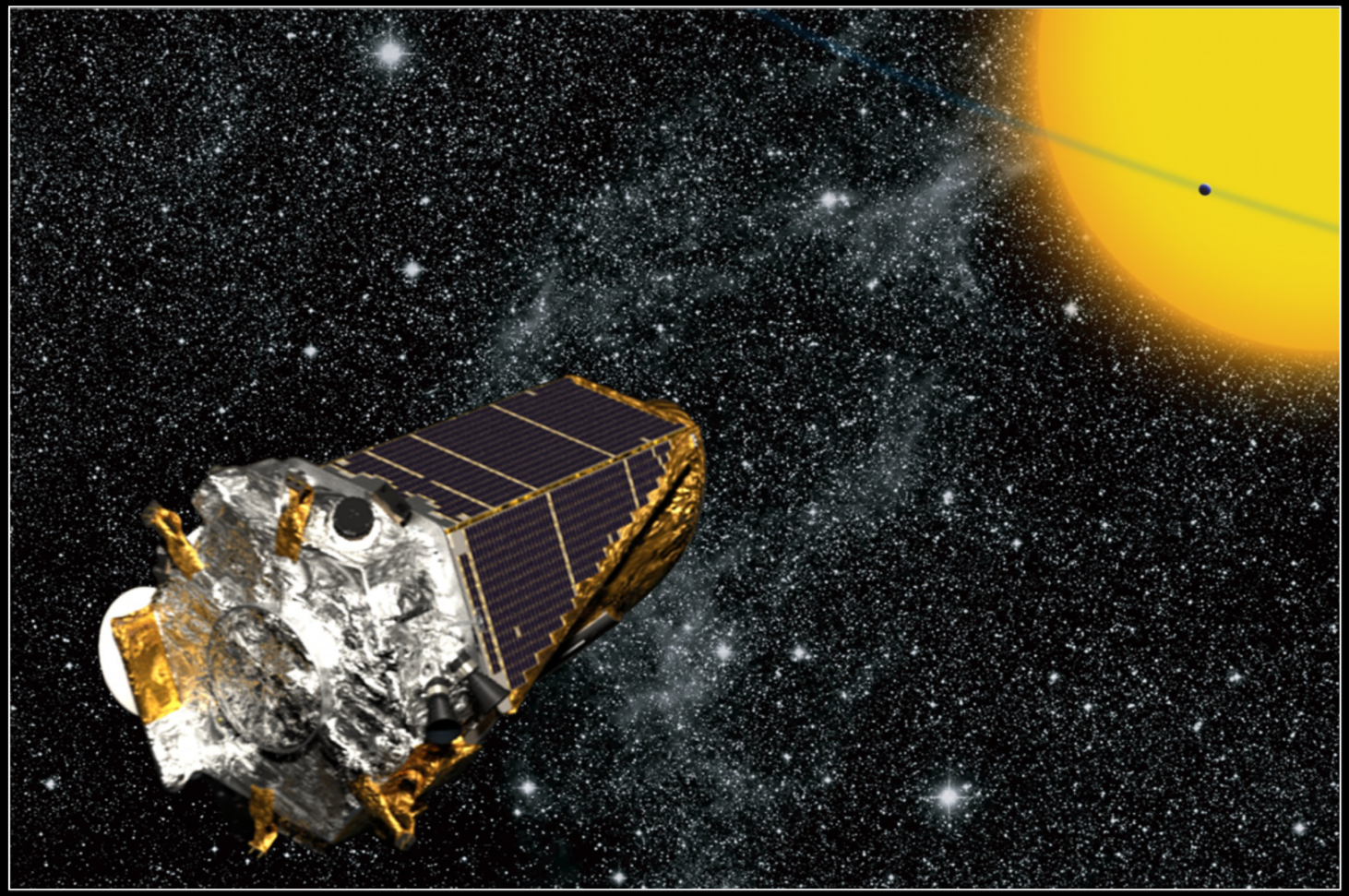
A Search for Habitable Planets

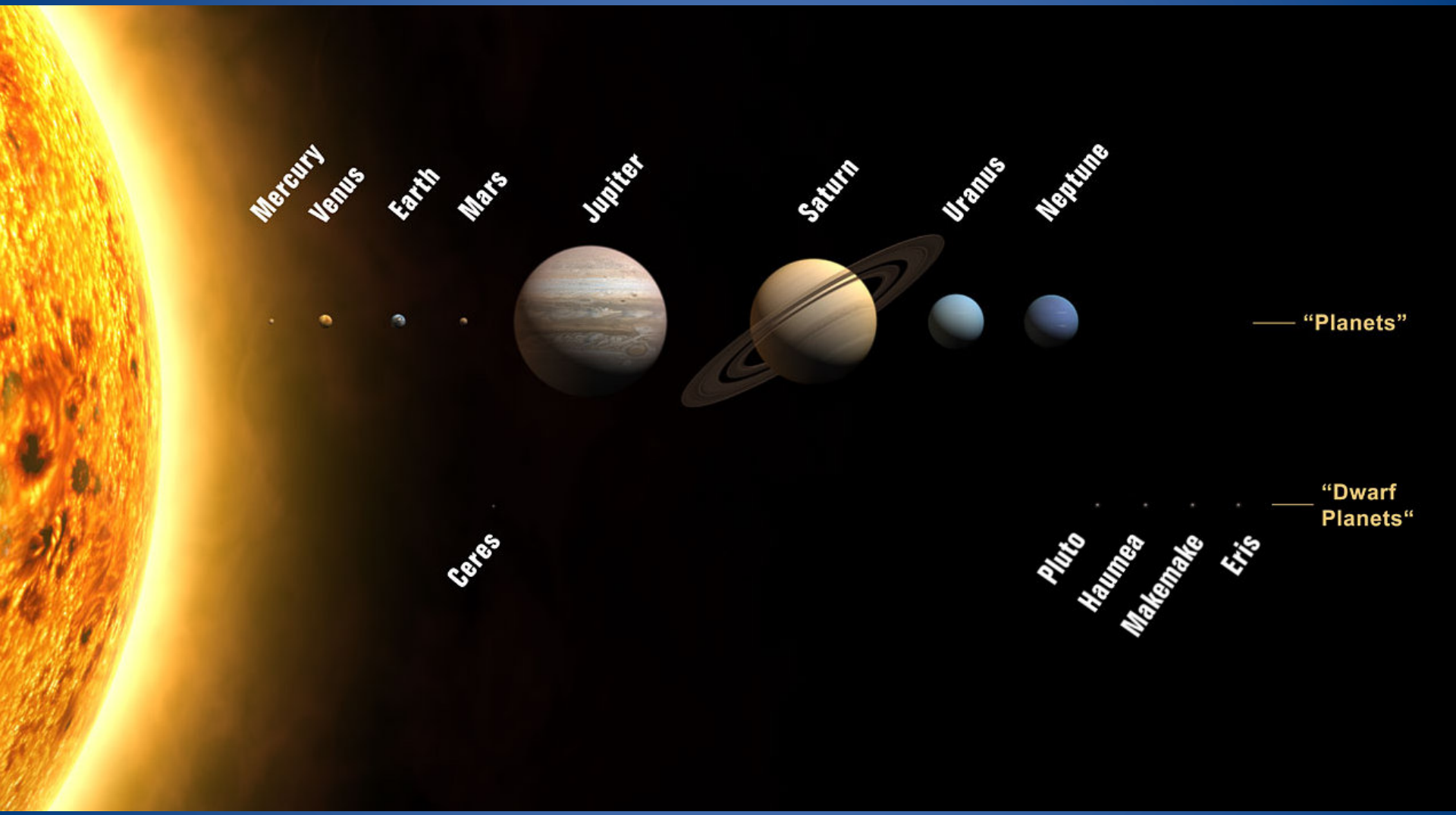
Transit Tracks:
Finding Extrasolar Planets

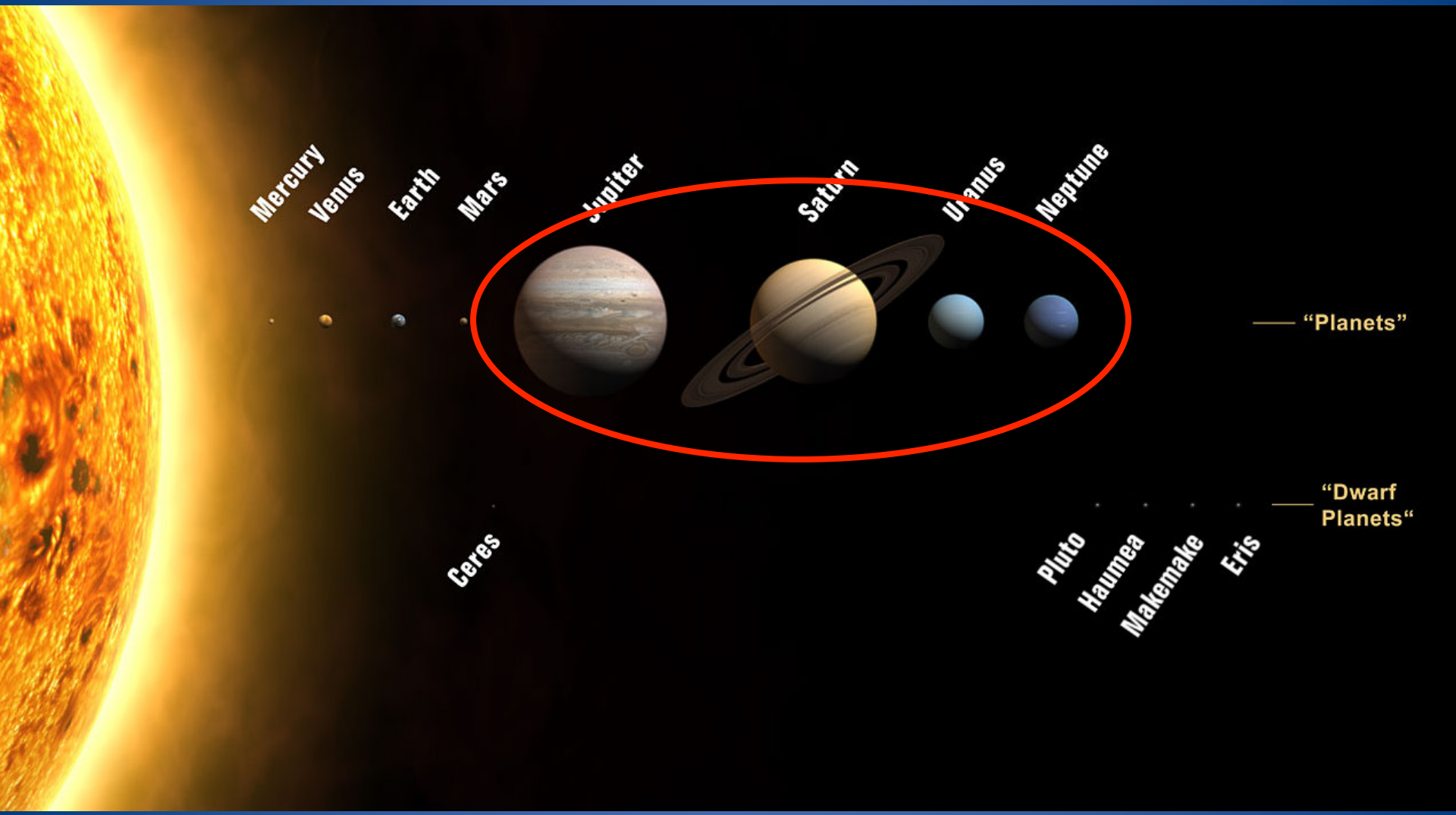
a science & math activity

Kepler Mission Goal

Kepler seeks evidence of Earth-size planets in the habitable zone of Sun-like stars.




Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
Ceres
Pluto
Haumea
Makemake
Eris
"Dwarf Planets"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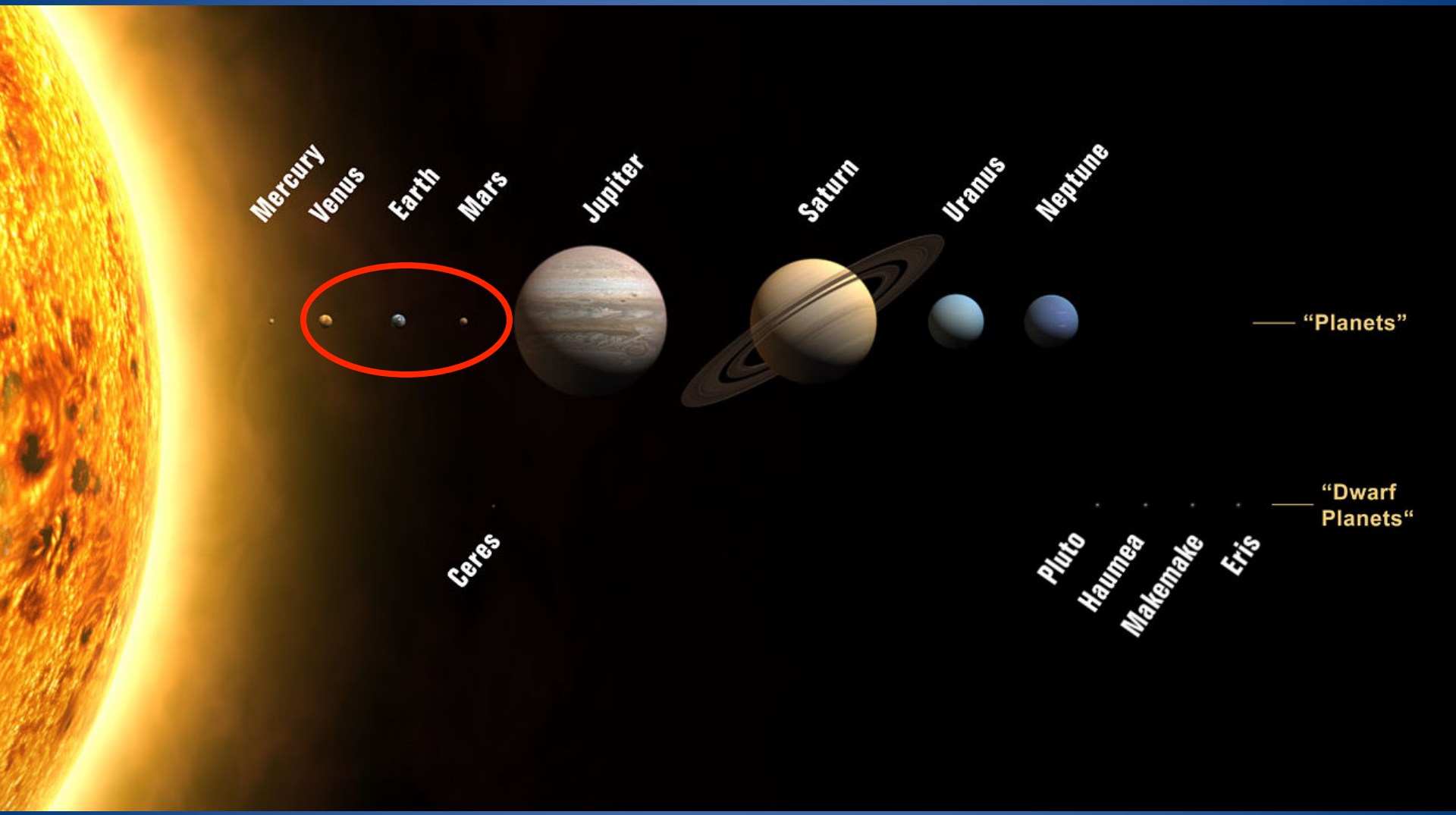
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What is Earth-size & Sun-size?

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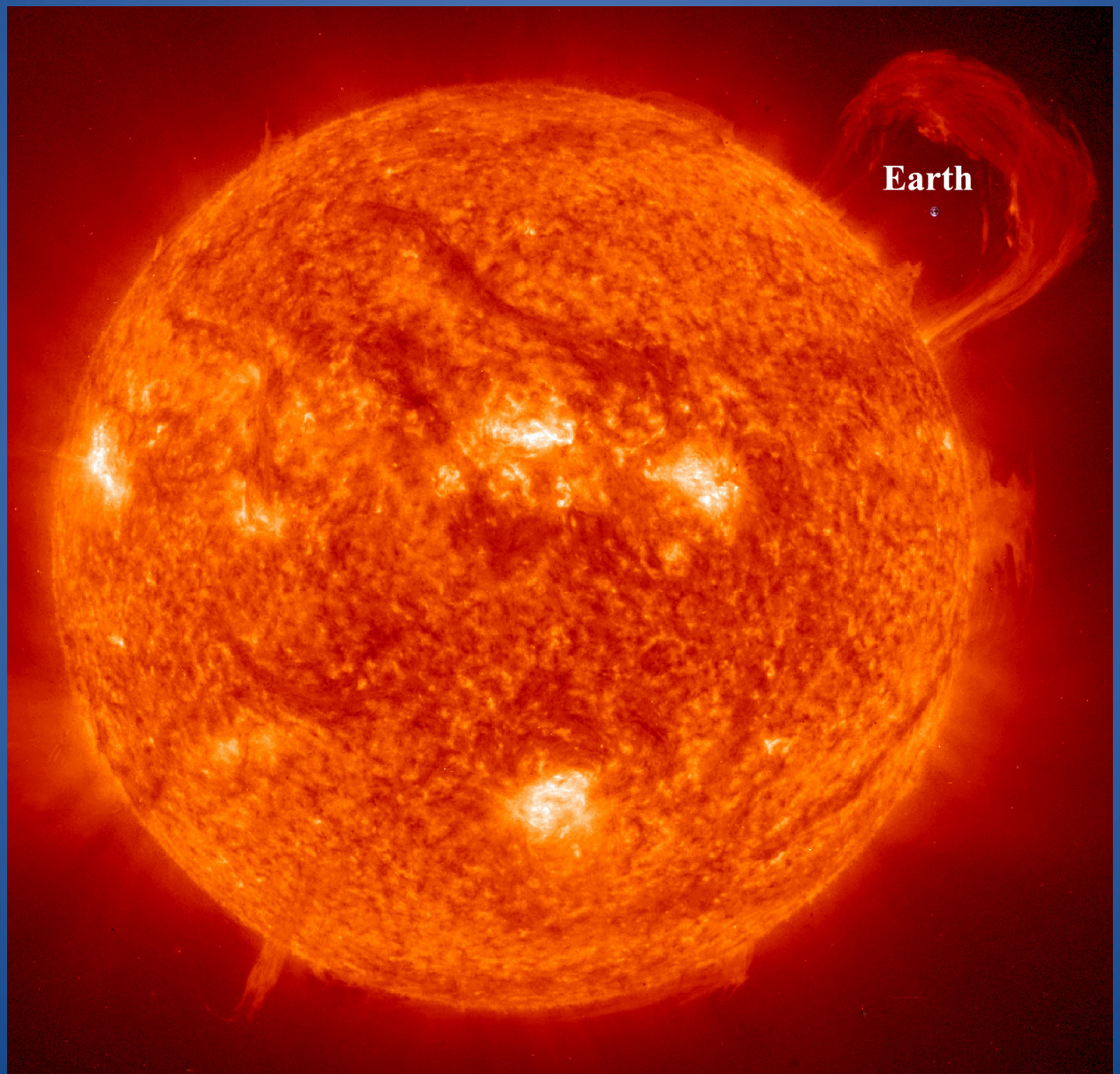

What is the habitable zone?

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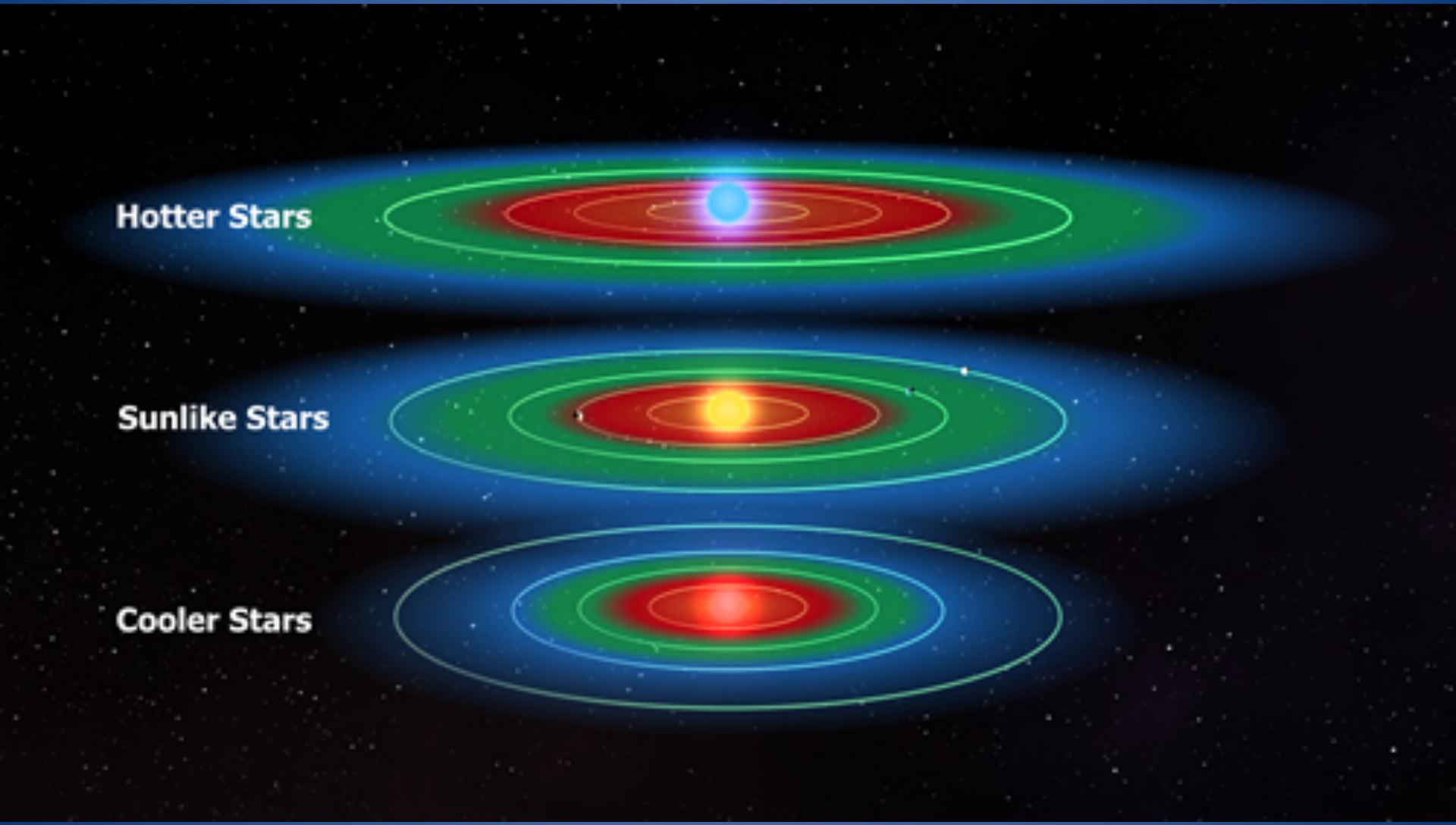

What is a “transit”?

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“transit”

Kepler

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“transit”

Kepler

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What's this?

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A transit of Venus across the Sun takes place when the planet Venus passes directly between the Sun and Earth, so that Venus blocks a small spot of the Sun's disk. Since the Sun is over 100 times larger in diameter than Venus, the spot is very small indeed.

Account of Jeremiah Horrock's observations of the transit of Venus

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An Englishman, Jeremiah Horrocks, made the first European observation of a transit of Venus from his home in Much Hoole, England, in the winter of 1639. Horrocks had read about Johannes Kepler who predicted transits in 1631 and 1761, and a near miss in 1639 when Venus would pass very close to the Sun, but not actually in front of it. Horrocks made corrections to Kepler's calculation for the orbit of Venus and predicted that 1639 would not be a near miss, but an actual transit. He was uncertain of the exact time, but calculated that the transit would begin about 3:00 pm. He focused the image of the Sun through a simple telescope onto a card, where the image could be safely observed.

After watching for most of the day with clouds obscuring the Sun often, he was lucky to see the transit as clouds cleared at about 3:15 pm, just half an hour before sunset. The observations allowed him to make a well-informed estimate as to the size of Venus, but more importantly, using geometry, to calculate the distance between the Earth and the Sun which had not been known accurately at that time. He was the first of many people who used transit observations to try to determine the distance from the Sun to the Earth.

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Imagine you have a light sensor aimed a lamp.

What would the transit of a book look like if you made a graph of brightness vs time?

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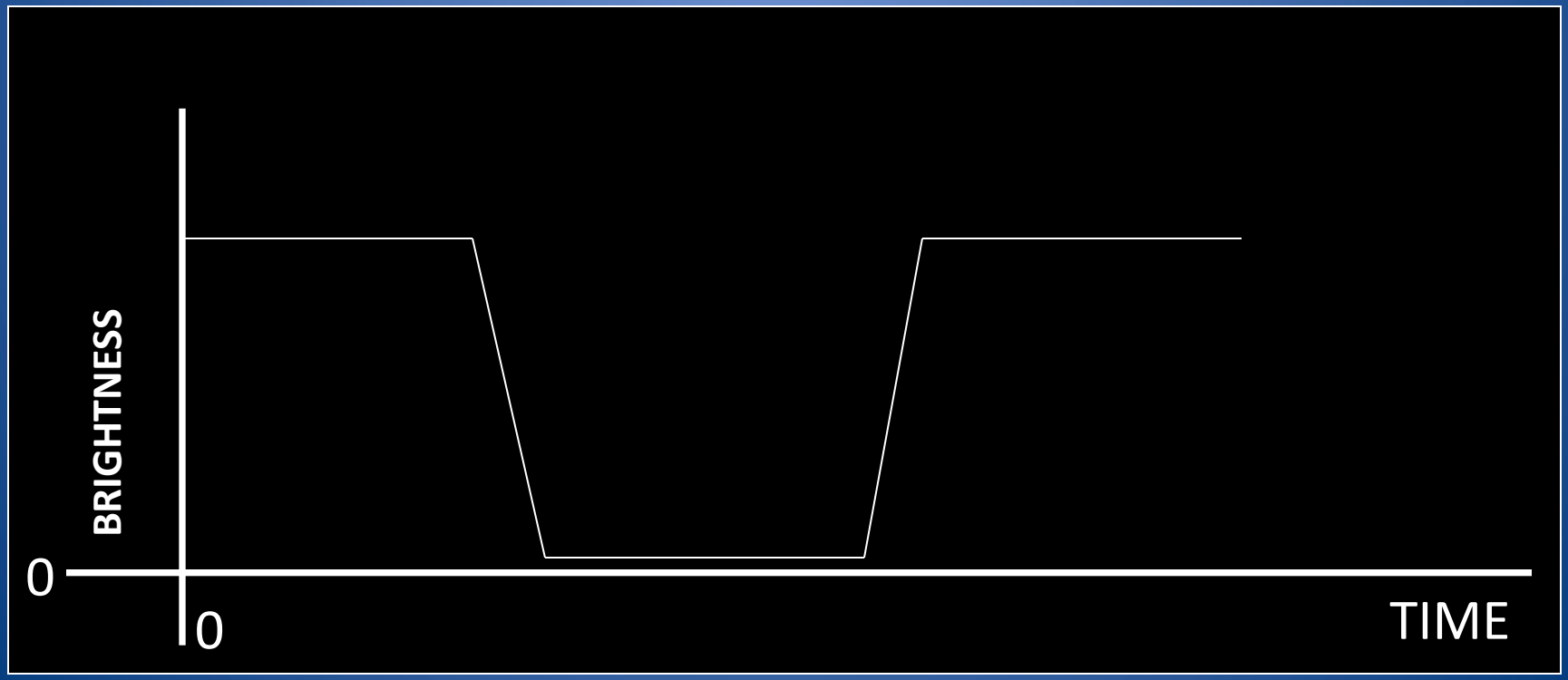
Like this?



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What would the transit of a planet look like if you made a graph brightness vs time?

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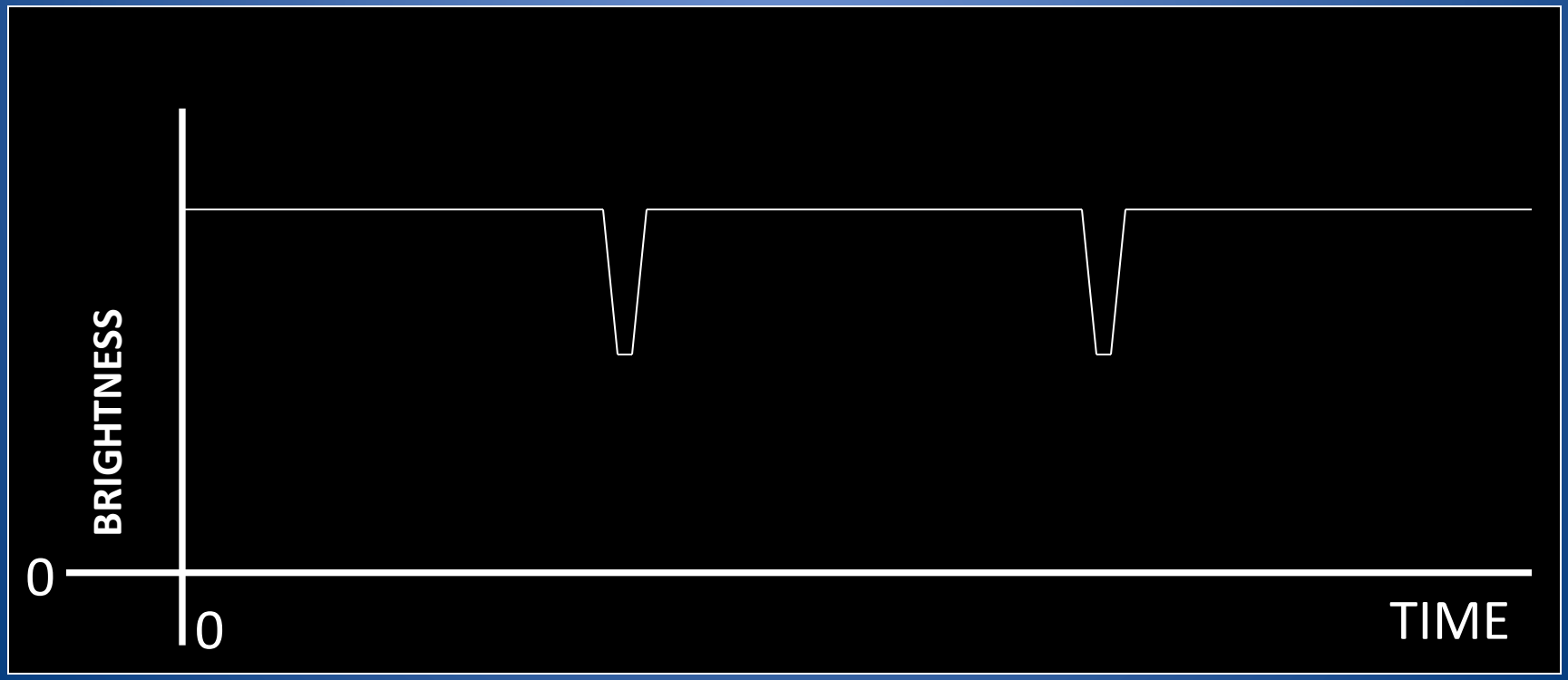
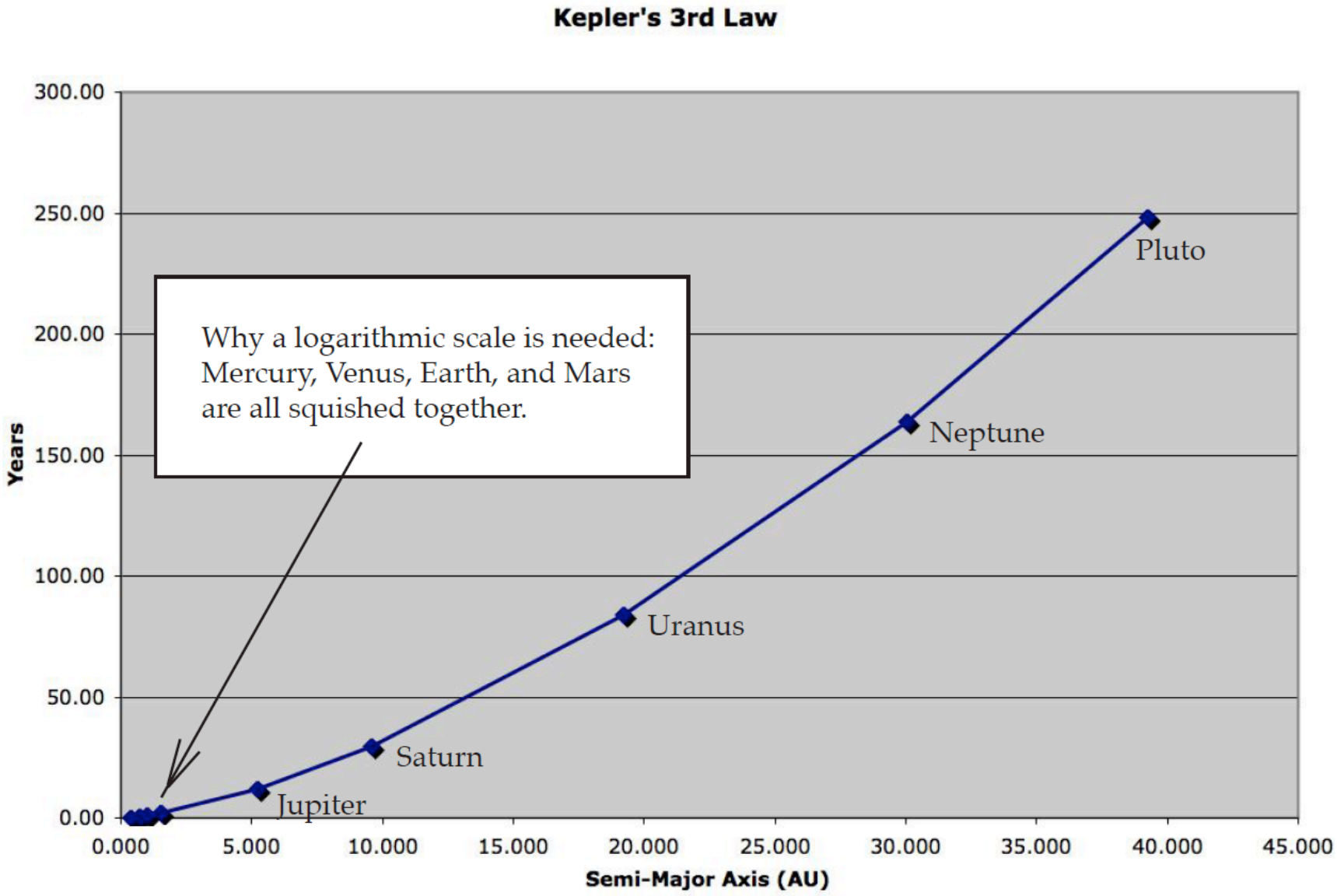
This is a “light curve.”

How are the planet’s size and orbital period shown in the light curve?

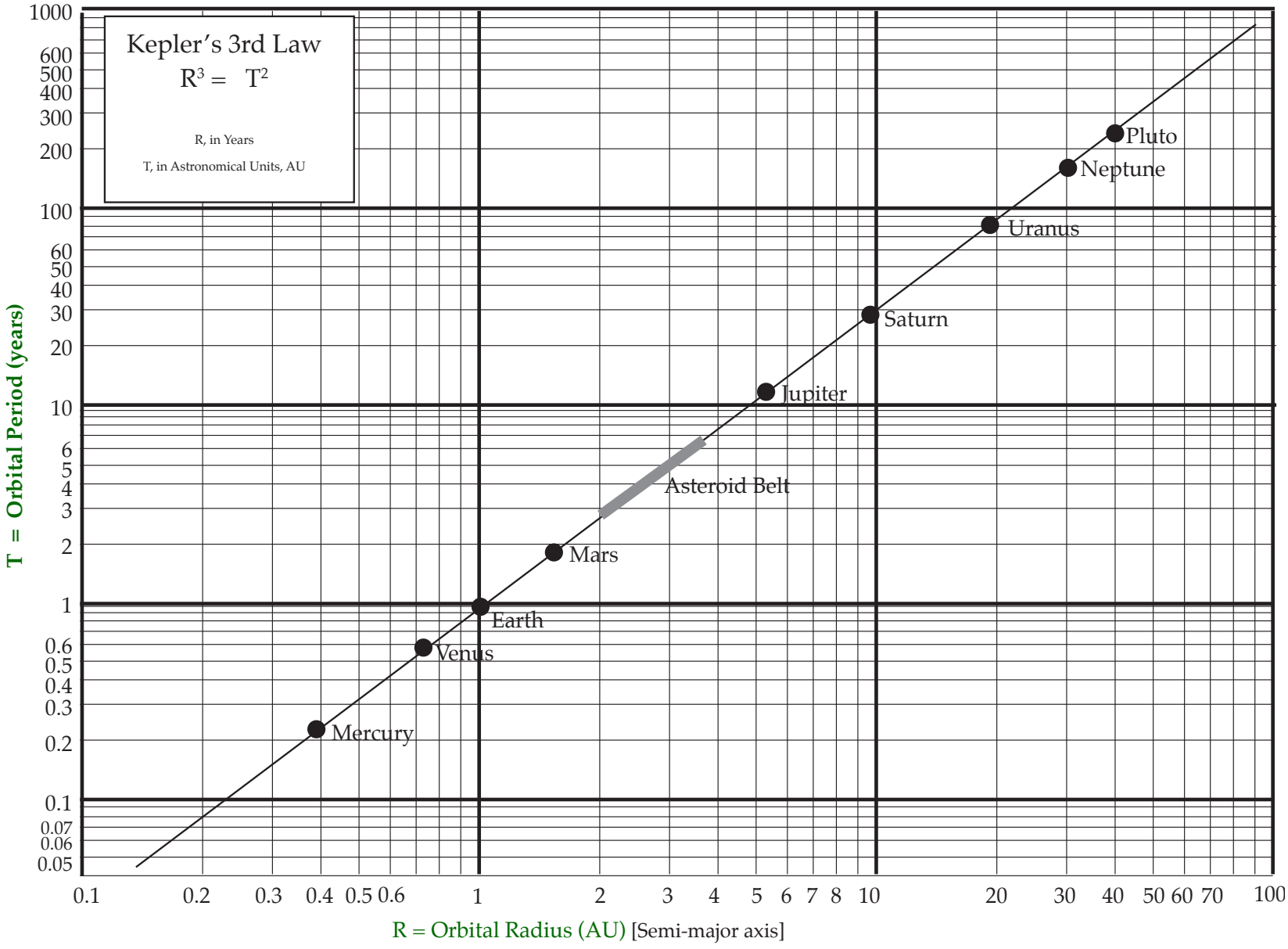


Is there a relationship between the planet's period
(time for one orbit)
and
its distance from its star?

Linear Plot: Kepler's 3rd Law



Keplers's 3rd Law Graph of Whole Solar System with Logarithmic Scales



Note: All objects -- planets, moons, asteroids, comets, meteoroids, dwarf planets -- all obey Kepler's 3rd Law.

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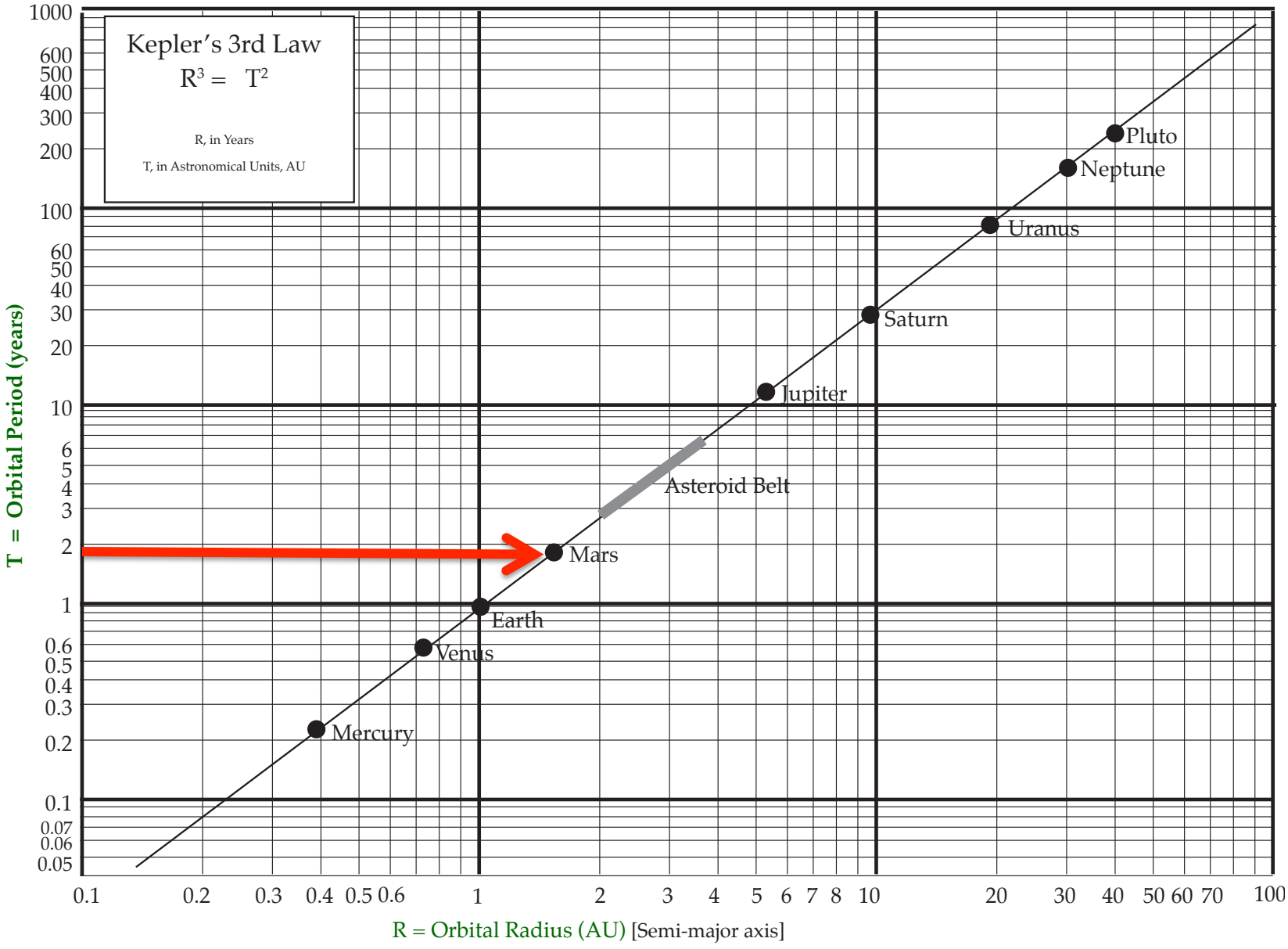

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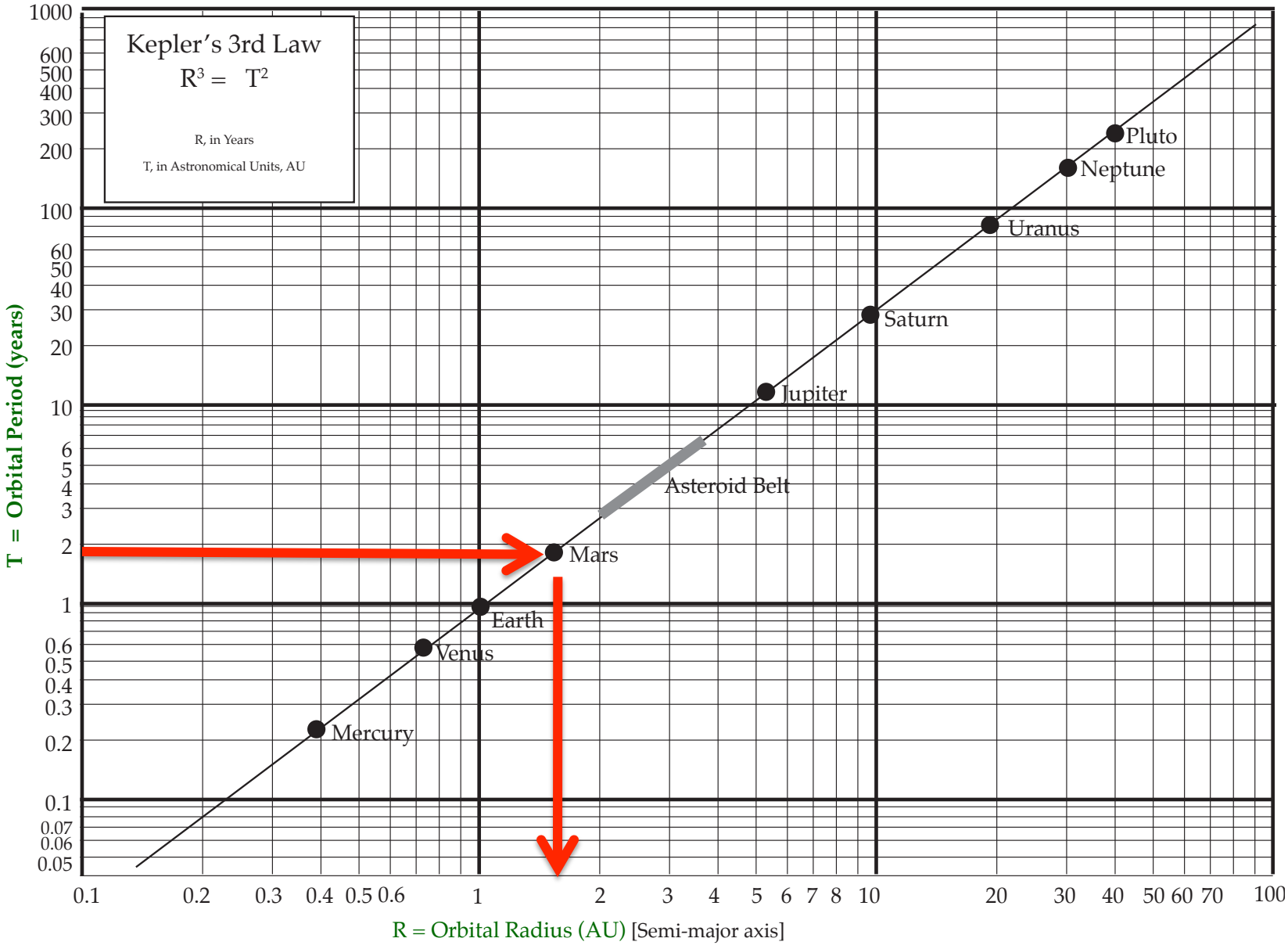
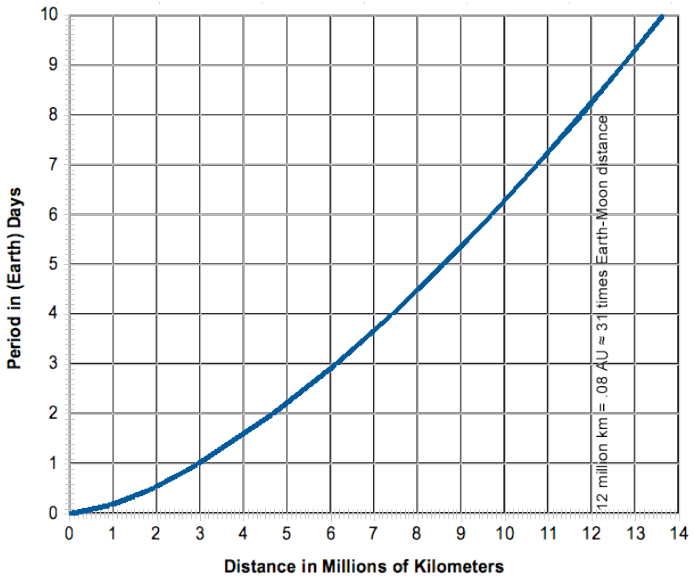


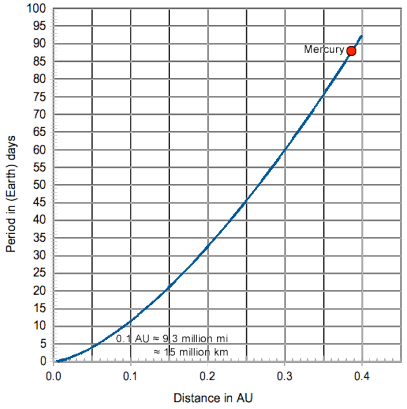
Note: All objects -- planets, moons, asteroids, comets, meteoroids, dwarf planets -- all obey Kepler's 3rd Law.

Kepler's 3rd Law Graphs

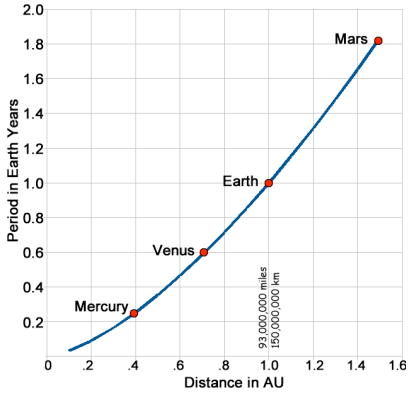
Kepler's 3rd Law Graph for Periods less than 10 days



Kepler's 3rd Law Graph for Periods Less Than 100 Days

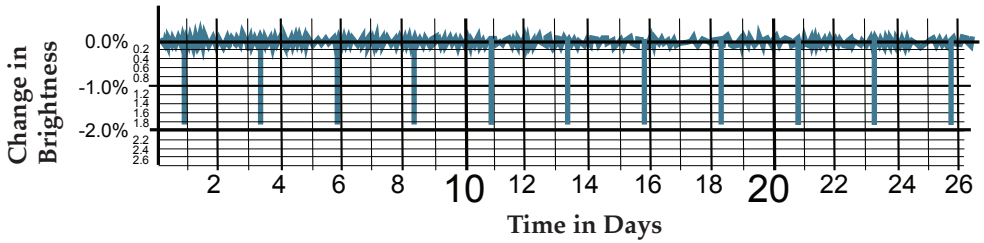


Kepler's 3rd Law Graph for the Inner Solar System (periods less than 2 years)

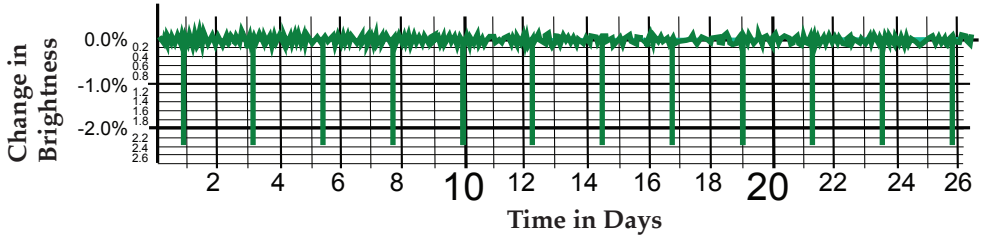


Transit Light Curves

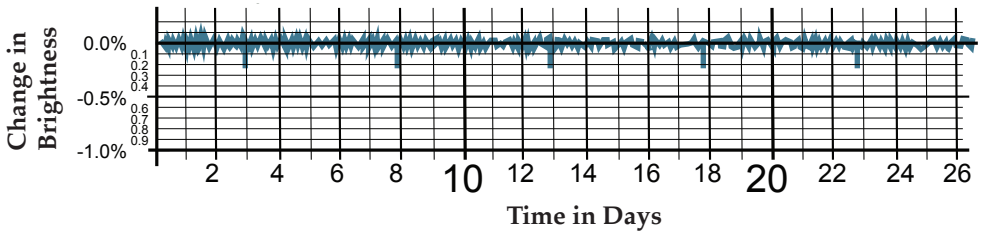
Kepler-1b (TrES-2)



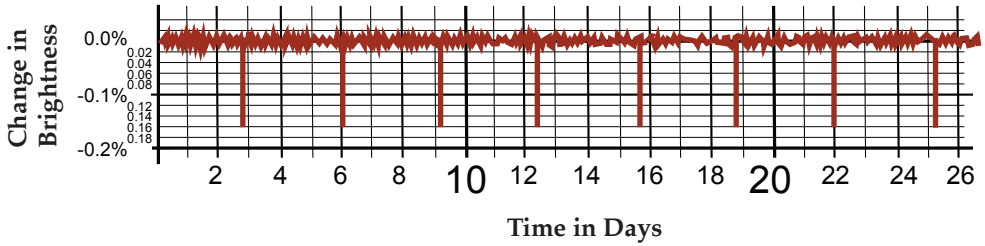
Kepler-2b (HAT-P 7b)

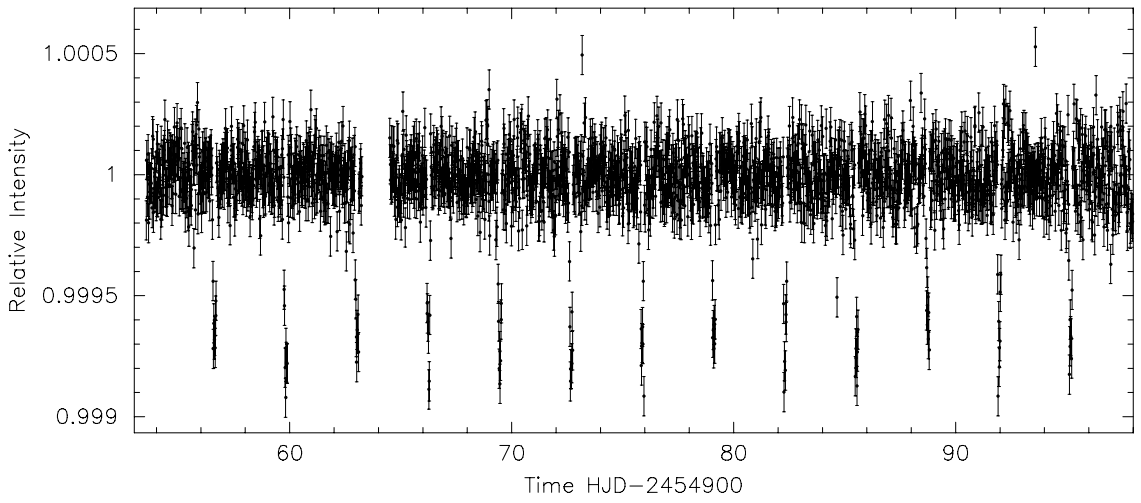


Kepler-3b (HAT-P-11b)



Kepler-4b

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0.999
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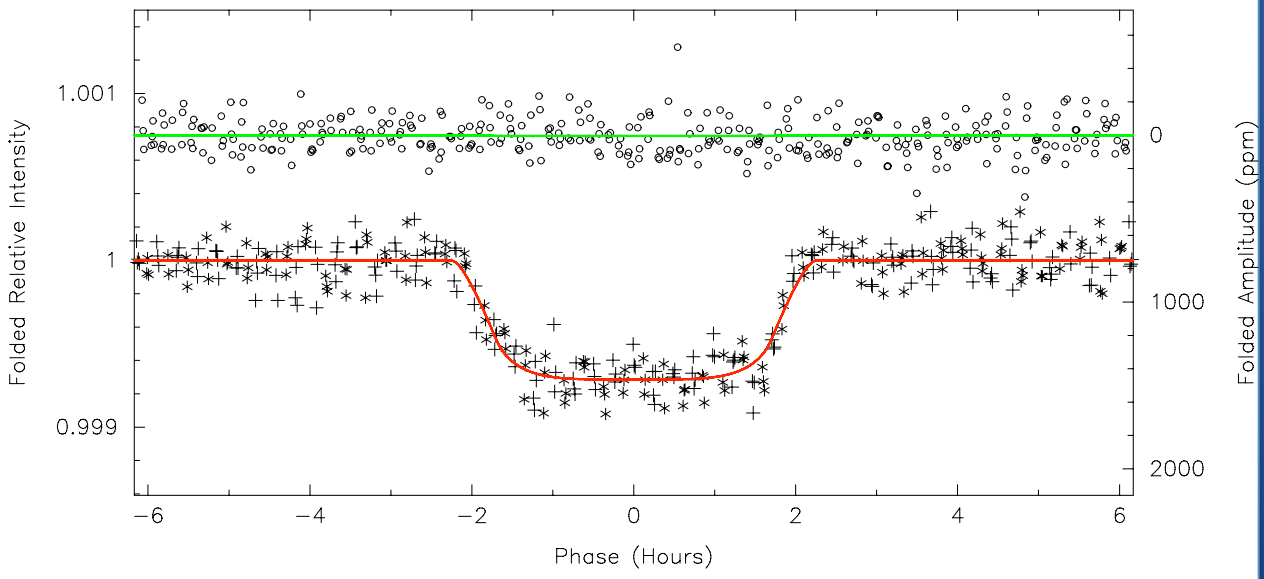
Time HJD−2454900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1
0.999
Folded Relative Intensity
0
1000
2000
Folded Amplitude (ppm)
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−2
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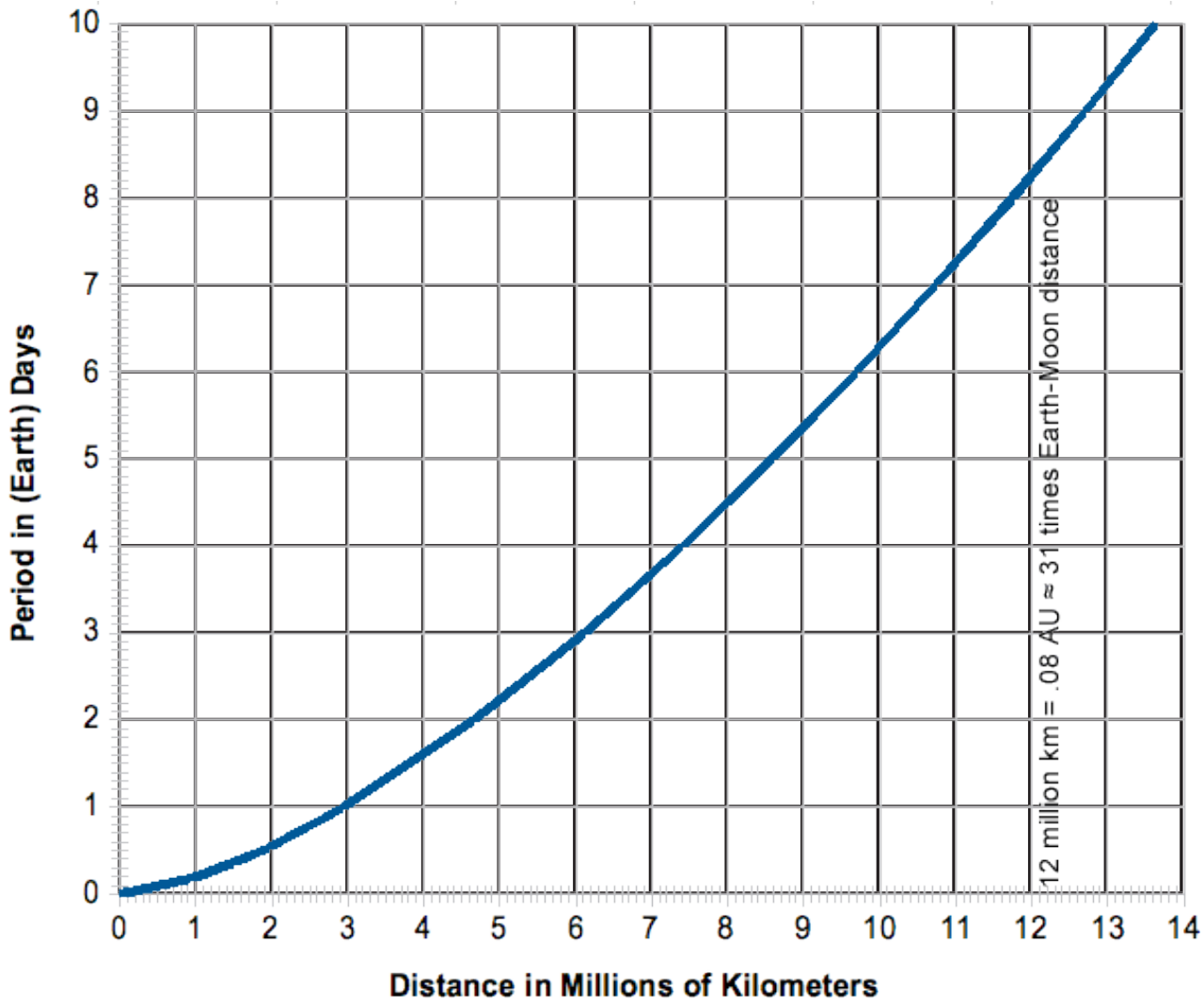
4
6
Phase (Hours)

Kepler's 3rd Law Graph for Periods less than 10 days



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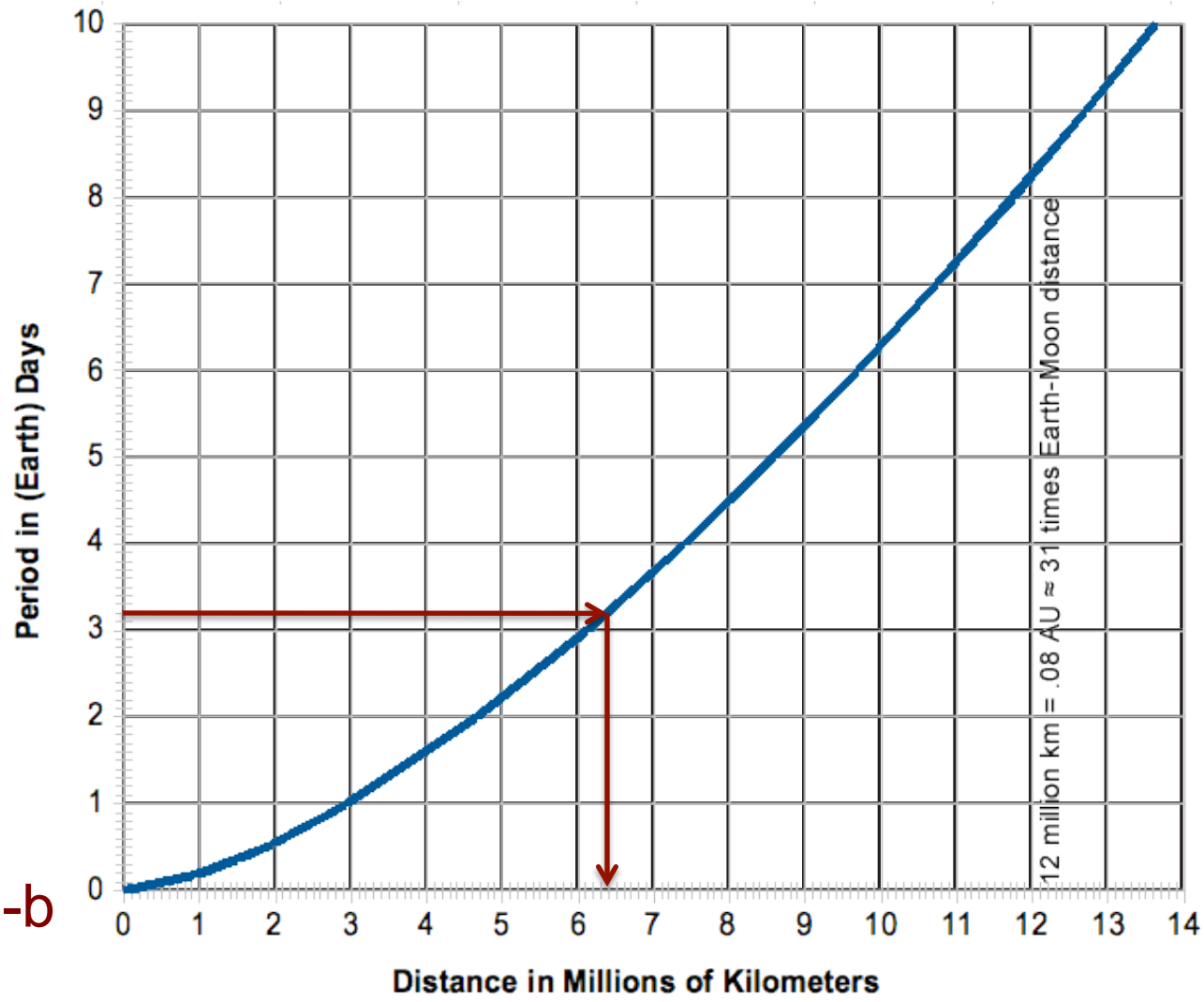
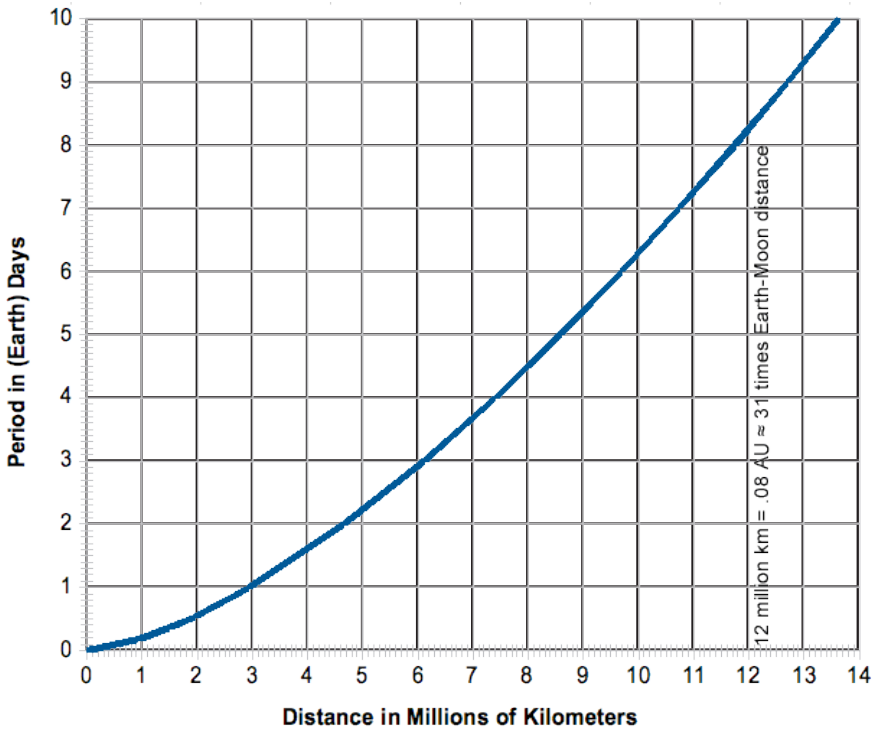


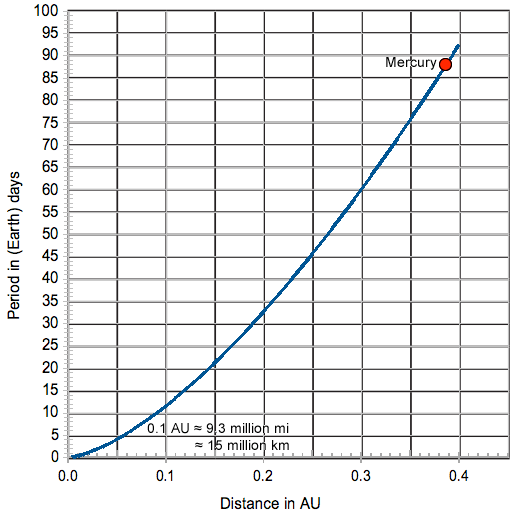
Kepler 4-b

Kepler's 3rd Law Graphs

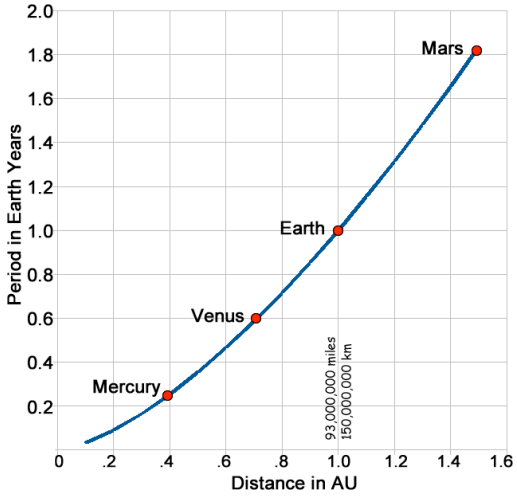
Kepler's 3rd Law Graph for Periods less than 10 days



Kepler's 3rd Law Graph for Periods Less Than 100 Days



Kepler's 3rd Law Graph for the Inner Solar System (periods less than 2 years)



Transit Light Curves

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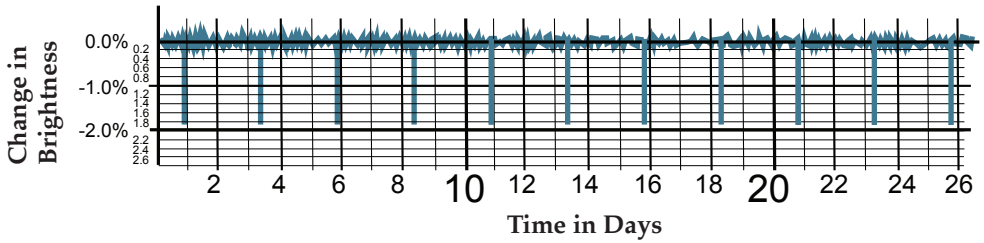

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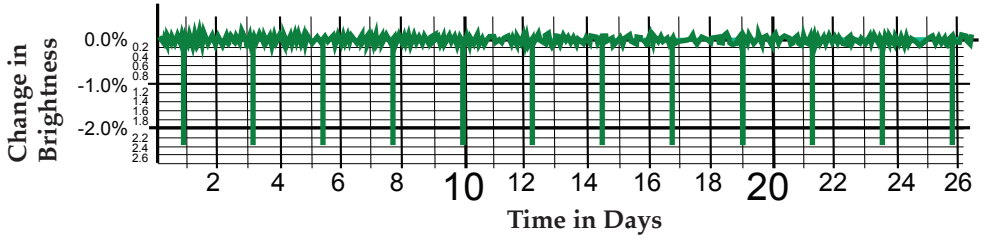

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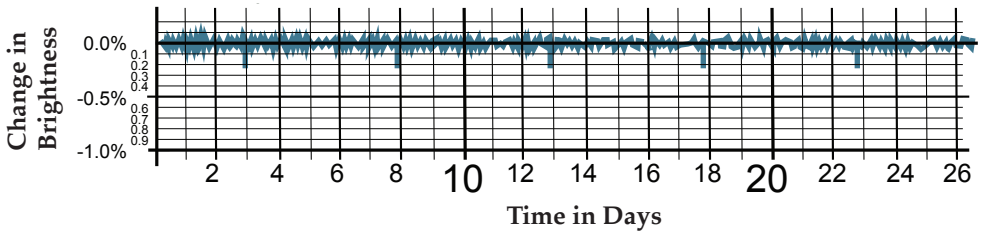
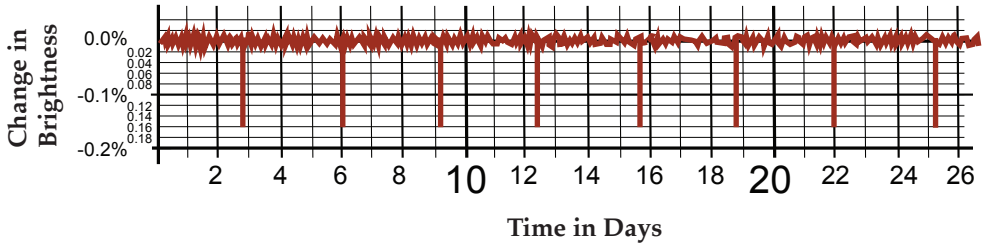
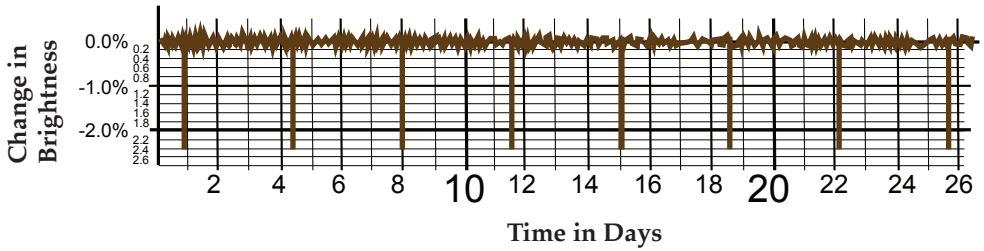


Kepler-4b

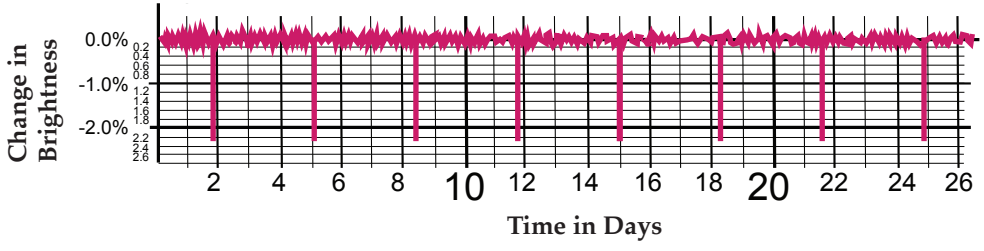


Transit Light Curves

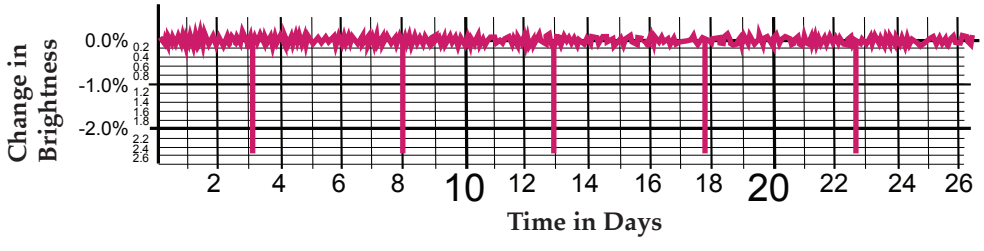
Kepler-5b



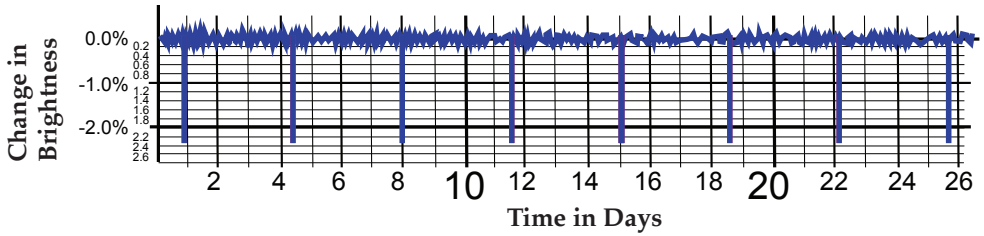
Kepler-6b



Kepler-7b

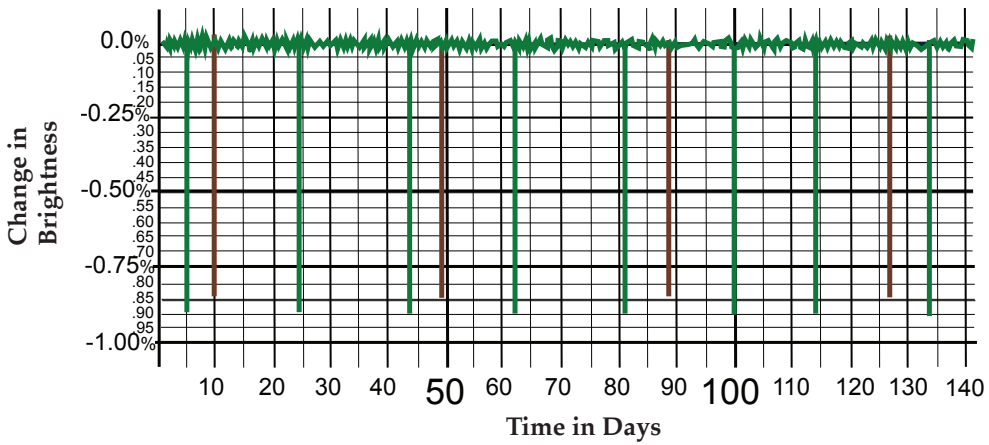


Kepler-8b

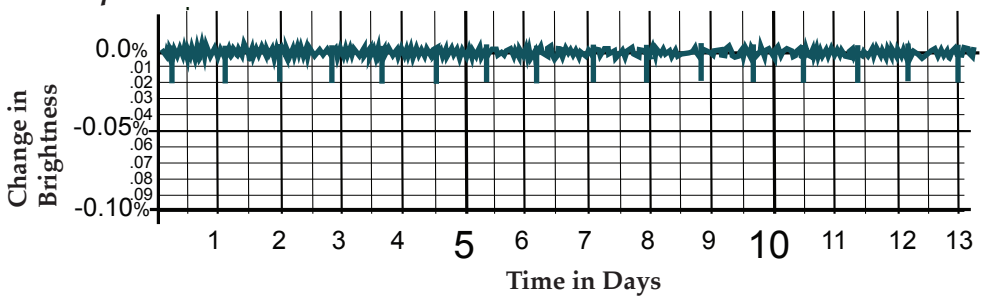


Transit Light Curves

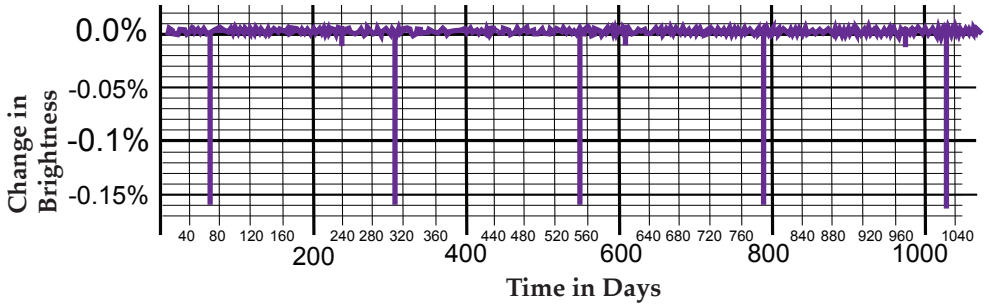
Kepler-9b, 9c



Kepler-10b

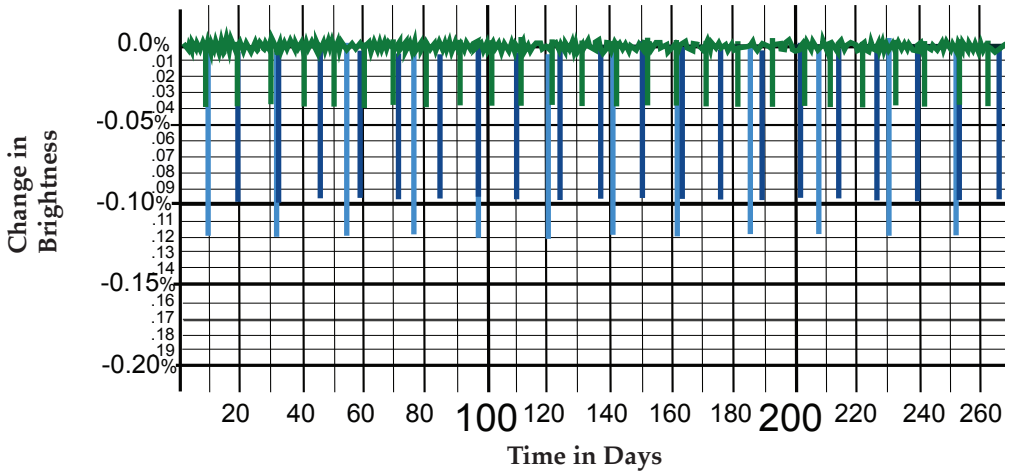


Mystery

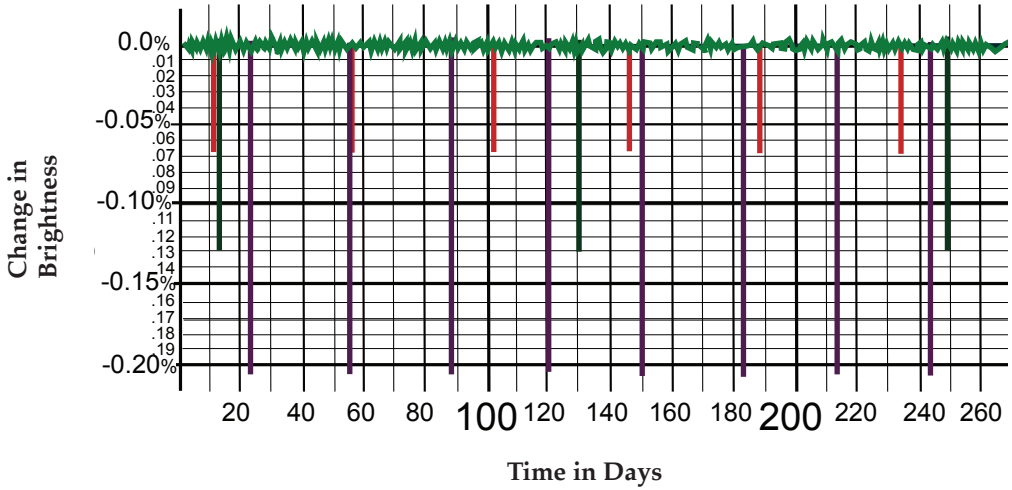


Transit Light Curves

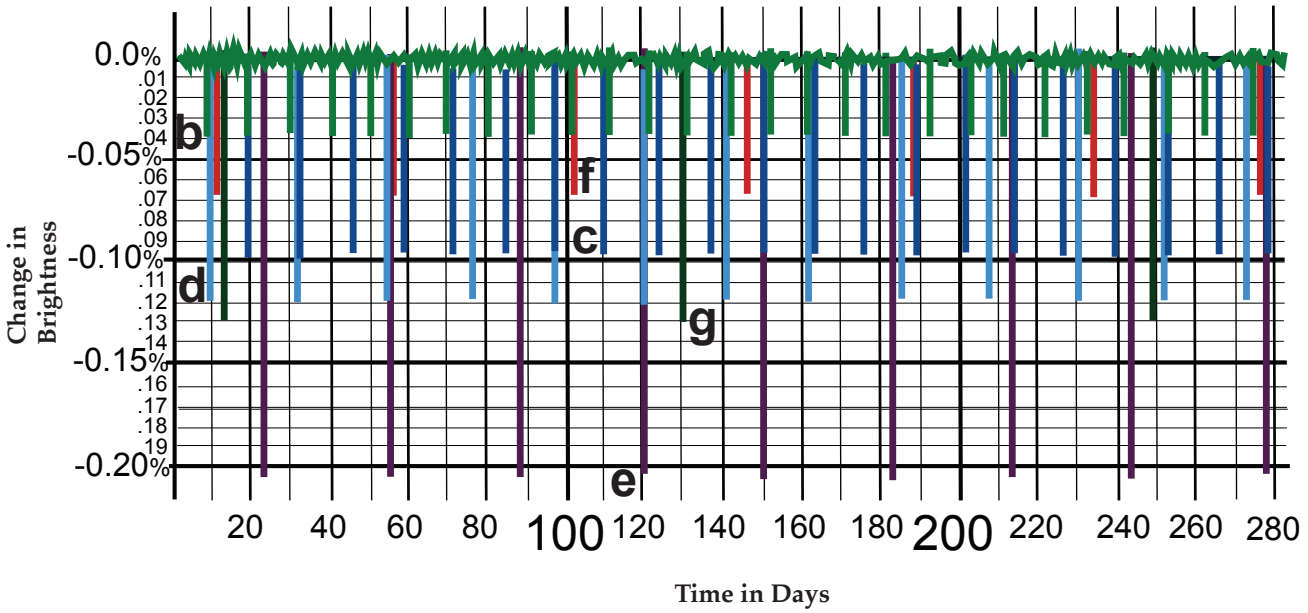
Kepler-11b, 11c, 11d



Kepler-11e, 11f, 11g



Kepler-11b, 11c, 11d, 11e, 11f, 11g



Analyzing Light Curves

Names: _____

Instructions: The "Transit Light Curves" are graphs of NASA's Kepler Mission's observations of stars. They show how the light level changes when a planet transits in front of a star. Study the light curves to find the period of the planet.The period is the time between transits and is year-length for a planet. Use "Kepler's 3rd Law Graphs" to find the "Orbital Distance" of the planet from its parent star.

The "Planet's Size" is found by measuring the "Change in Brightness," the small percentage drop in the light level as the planet transits. Calculate the planet's radius using the formula in the table below.

Orbital Distance

(from Kepler's 3rd Law graph)

Planet Name	Period Units _____	Orbital Distance Units _____

Planet's Size

(planet radius using formula)

Planet	Brightness Drop of Z (%)	$\sqrt{Z}$	Radius = 10 x $\sqrt{Z}$ (in Earth radii)

Questions:

1. Which planet(s) are similar in size to Earth?

2. Jupiter's radius is about 11 times Earth's radius. Which planets are similar in size to Jupiter?

3. Describe the relationship between the period of the planets and their orbital distances.

Analyzing Light Curves: Calculated with Kepler's 3rd Law

Names: _____

Instructions: The "Transit Light Curves" are graphs of NASA's Kepler Mission's observations of stars. They show how the light level changes when a planet transits in front of a star. Study the light curves to find the period of the planet. The period is the time between transits and equals year-length for a planet (T).

Like Johannes Kepler did, we express the planet's distance (R) in **A**stronomical **U**nits (AU). 1 AU is the average distance from the Earth to the Sun.

For stars the same size as the Sun, Kepler's 3rd Law is simply:

$$R^3 = T^2 \quad * \quad \text{or} \quad R = \sqrt[3]{T^2 \cdot Ms}$$

For the Sun, Ms = 1. For other stars, Ms is mass in relationship to the Sun's mass.

The "Planet's Size" is determined by measuring the "Change in Brightness," the percentage drop in the light level as the planet transits. Calculate the planet's radius using the formula in the table below.

** Note: There is actually a constant K implied in this equation that sets the units straight:*
$R^3/T^2 = K$ *where* $K = 1\ AU^3/Year^2$

Orbital Distance
from Kepler's 3rd Law

Planet	Period (T) (T in years)	T^2	Ms	$R = \sqrt[3]{T^2 Ms}$ (in AU)

Planet's Size
(radius using formula)

Planet	Brightness Drop of Z (%)	$\sqrt{Z}$	Radius = 10 x $\sqrt{Z}$ (in Earth radii)

CUBE ROOTS

Number	Cube Root	Number	Cube Root	Number	Cube Root
0.0025	0.136	0.09	0.448	0.32	0.684
0.0050	0.171	0.1	0.464	0.34	0.698
0.0075	0.196	0.12	0.493	0.36	0.711
0.0010	0.100	0.14	0.519	0.38	0.724
0.0100	0.215	0.16	0.543	0.4	0.737
0.02	0.271	0.18	0.565	0.5	0.794
0.03	0.311	0.2	0.585	0.6	0.843
0.04	0.342	0.22	0.604	0.7	0.888
0.05	0.368	0.24	0.621	0.8	0.928
0.06	0.391	0.26	0.638	1	1.000
0.07	0.412	0.28	0.654		
0.08	0.431	0.3	0.669		

For cube-root calculator instructions:
http://kepler.nasa.gov/education/cuberoot/

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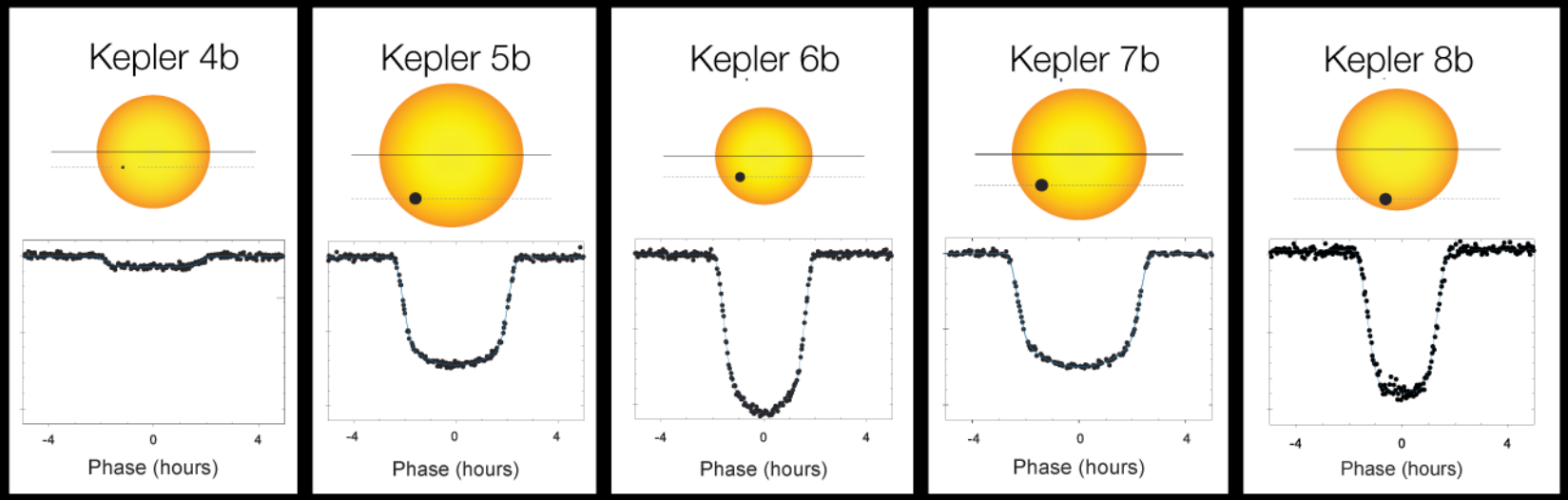
Kepler

A Search for Habitable Planets

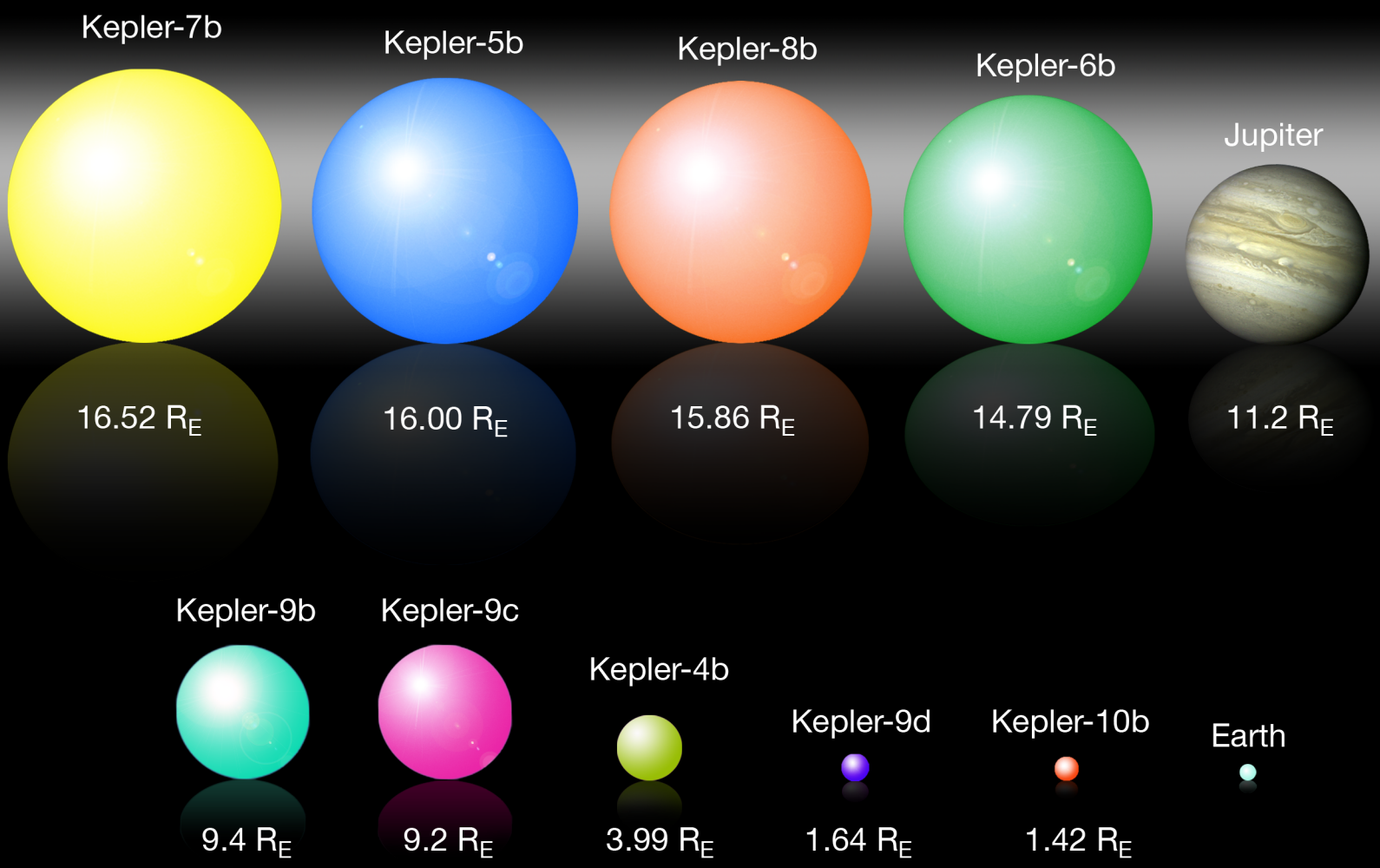
Planet Name	Period in days	Orbital Distance	Brightness Drop	$\sqrt{z}$	Radius = $10\sqrt{z}$

Transit Light Curves

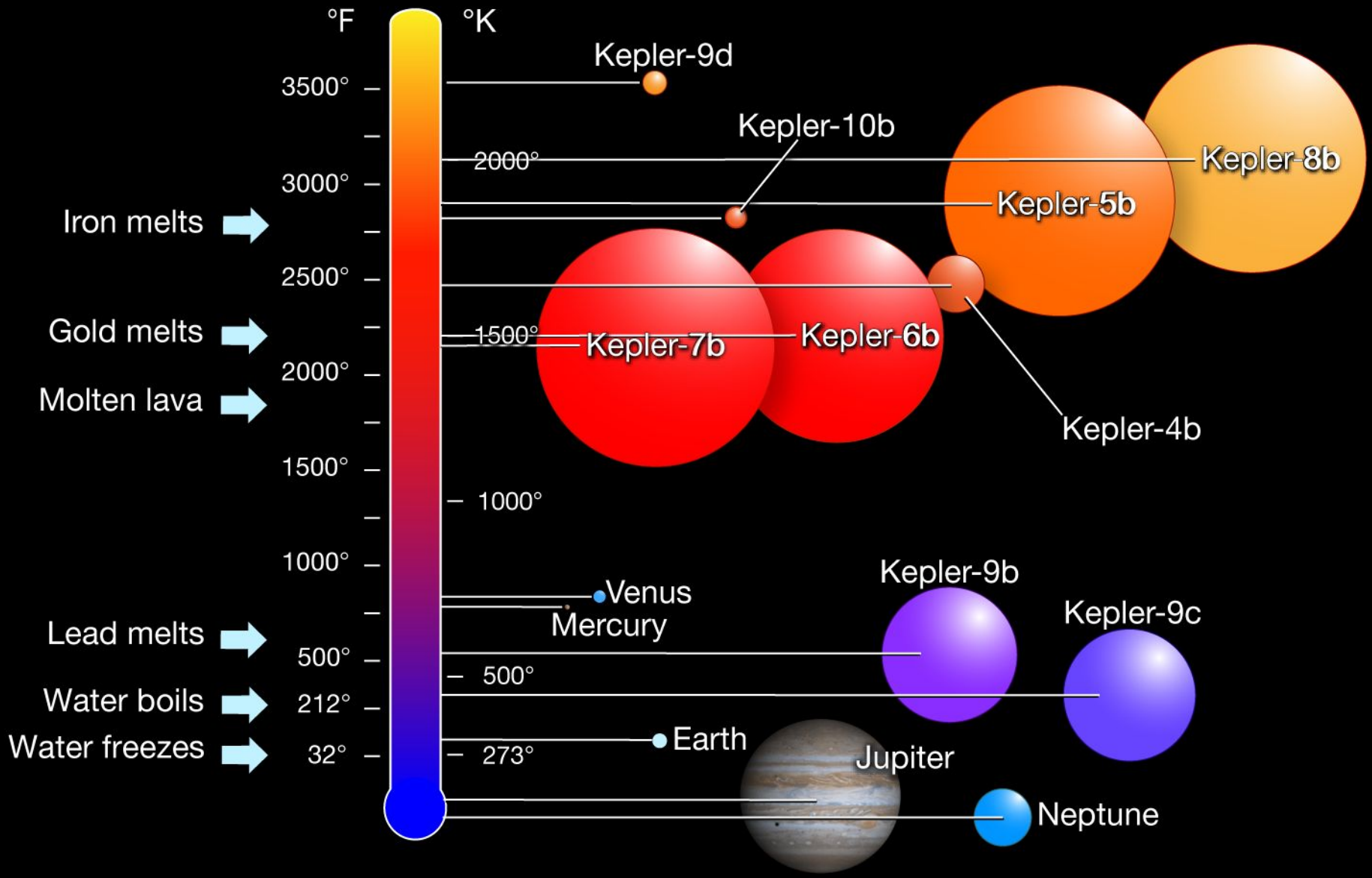


	Kepler 4b	Kepler 5b	Kepler 6b	Kepler 7b	Kepler 8b
Orbital Period (days)	*3.2 days*	*3.5 days*	*3.2 days*	*4.9 days*	*3.5 days*
Size (R_E)	*4.31*	*18.8*	*15.0*	*16.9*	*18.3*

Planet Size

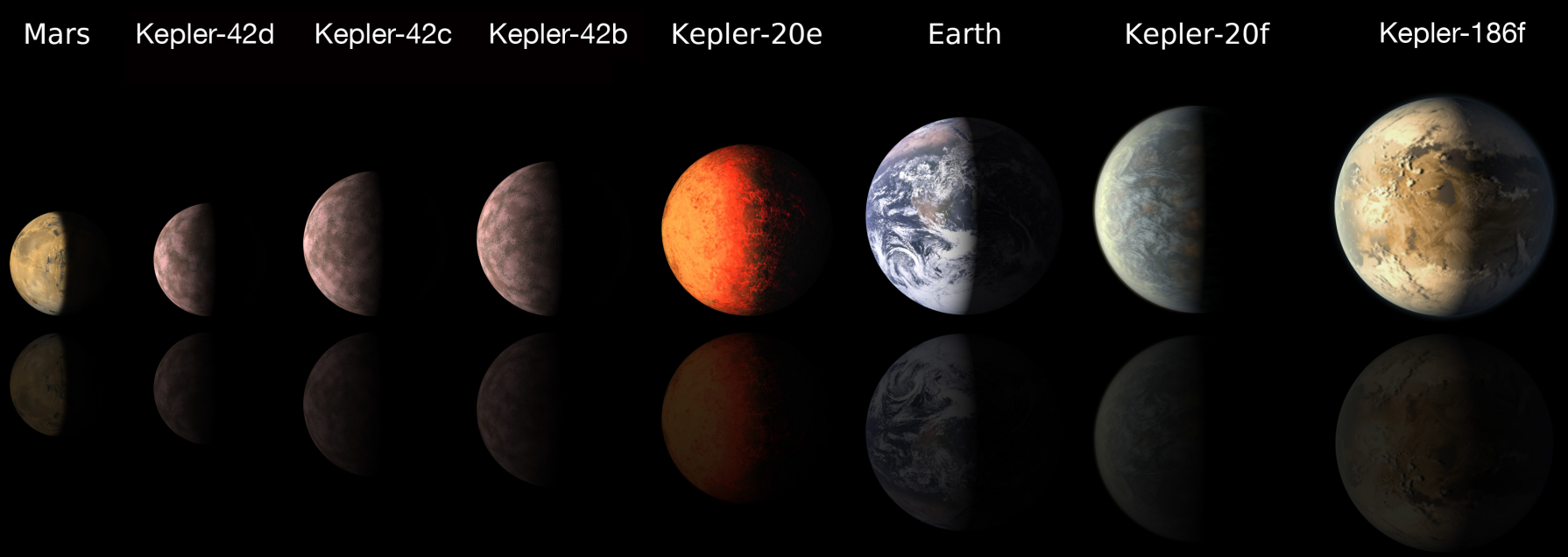

Kepler-7b
16.52 R_E
Kepler-5b
16.00 R_E
Kepler-8b
15.86 R_E
Kepler-6b
14.79 R_E
Jupiter
11.2 R_E
Kepler-9b
9.4 R_E
Kepler-9c
9.2 R_E
Kepler-4b
3.99 R_E
Kepler-9d
1.64 R_E
Kepler-10b
1.42 R_E
Earth

Planet Temperature & Size



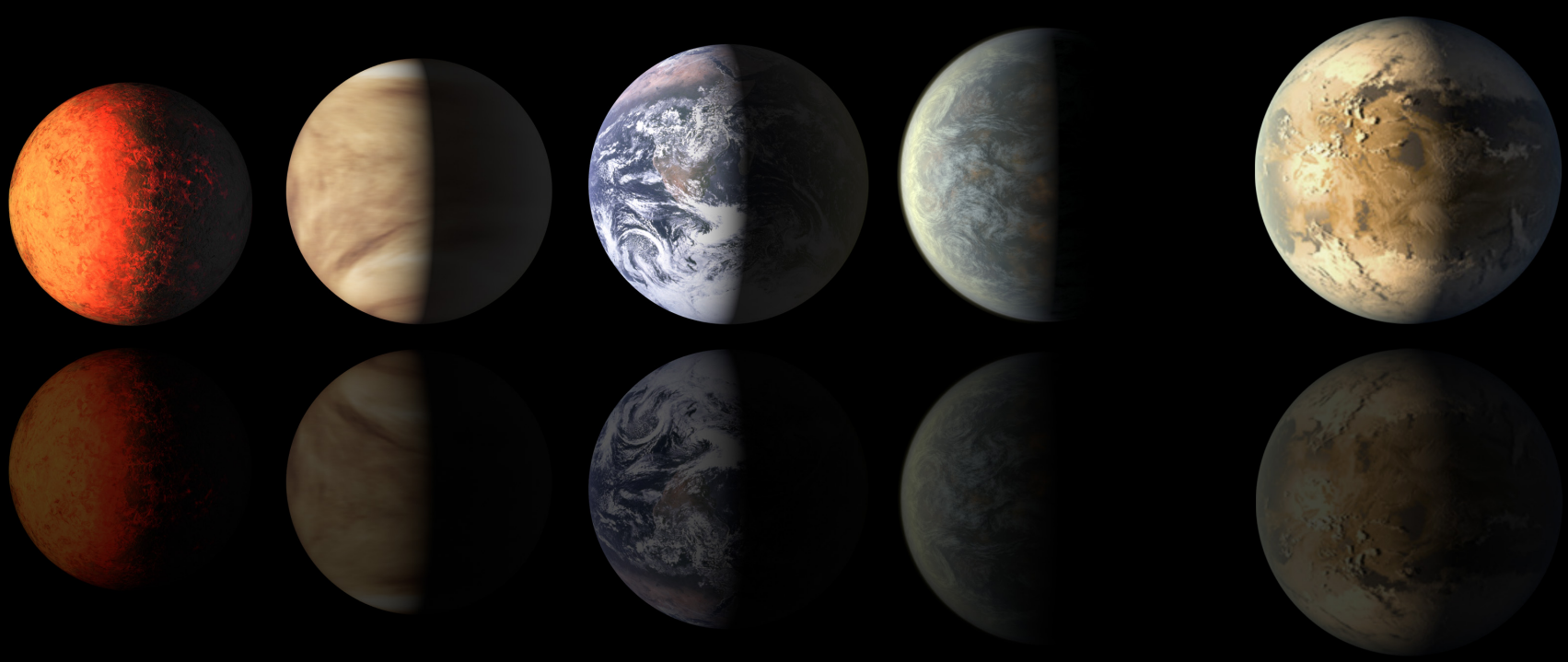
Planet Lineup

Kepler
A Search for Habitable Planets



Planet Lineup

Kepler
A Search for Habitable Planets



Kepler's Planet Candidates

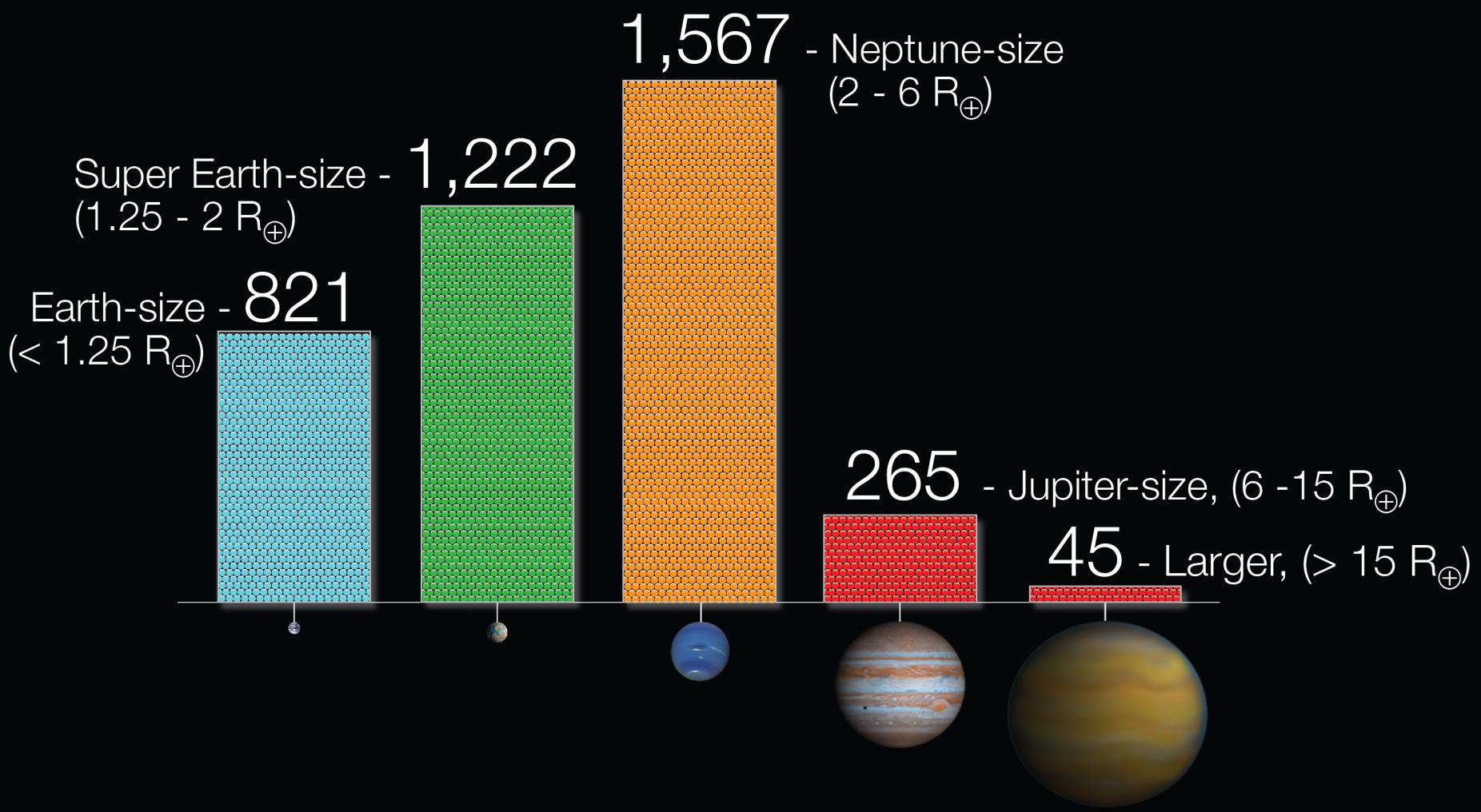
4,175 as of January 2015

By Location

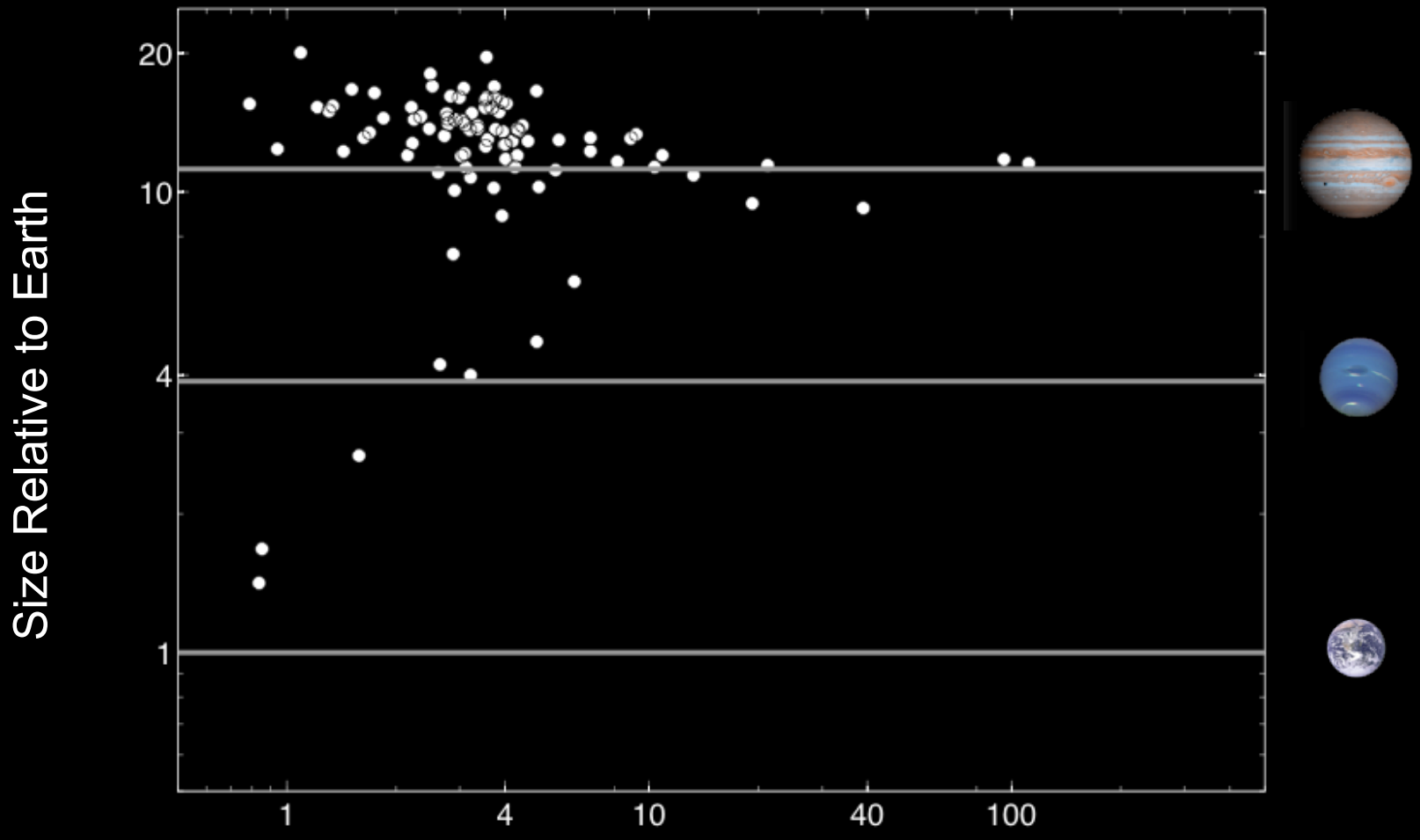
- Earth-size
- Super-Earth-size
- Neptune-size
- Jupiter-size and larger

Sizes of Planet Candidates

Totals as of September 2014

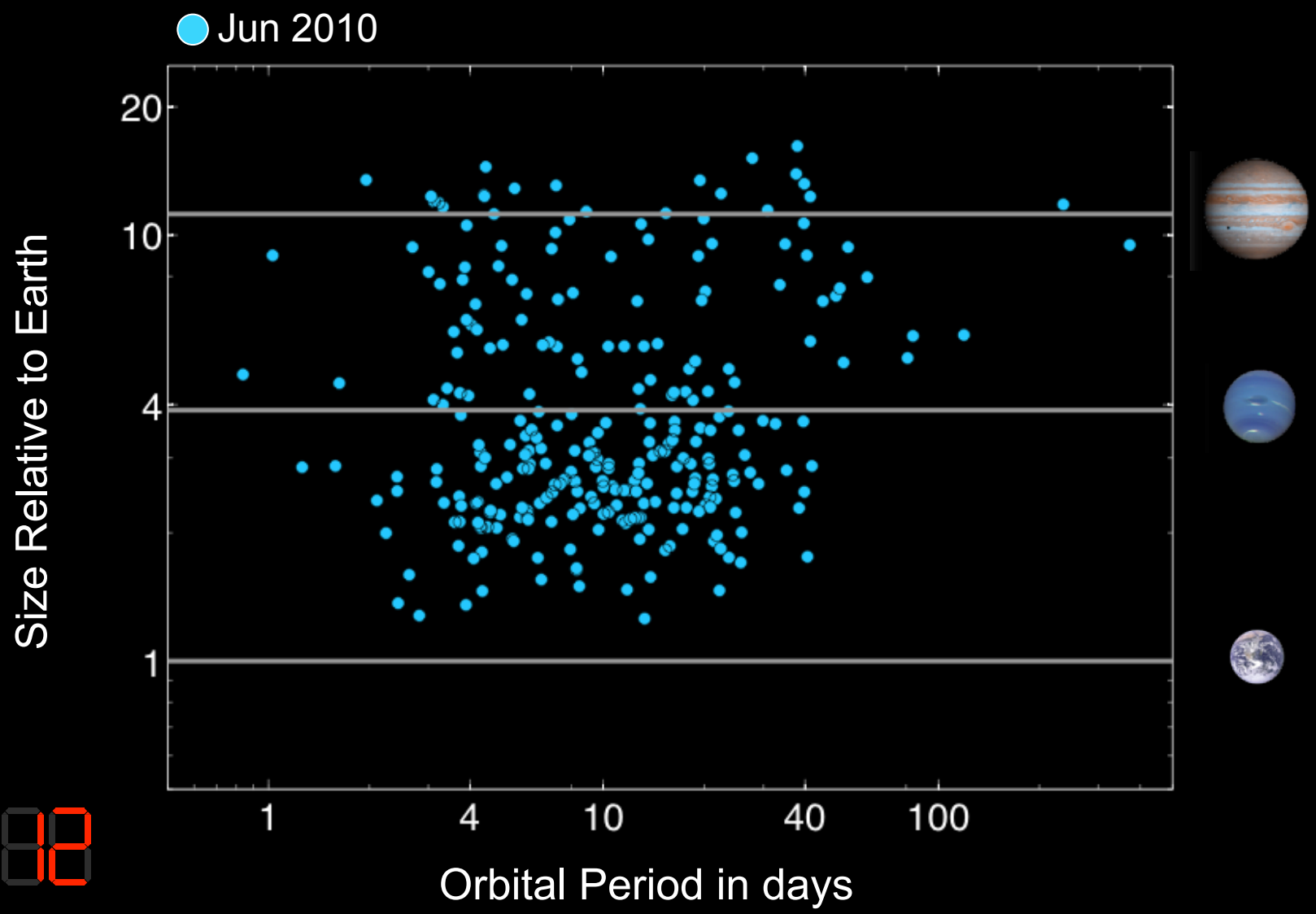


Transiting Planets pre-Kepler



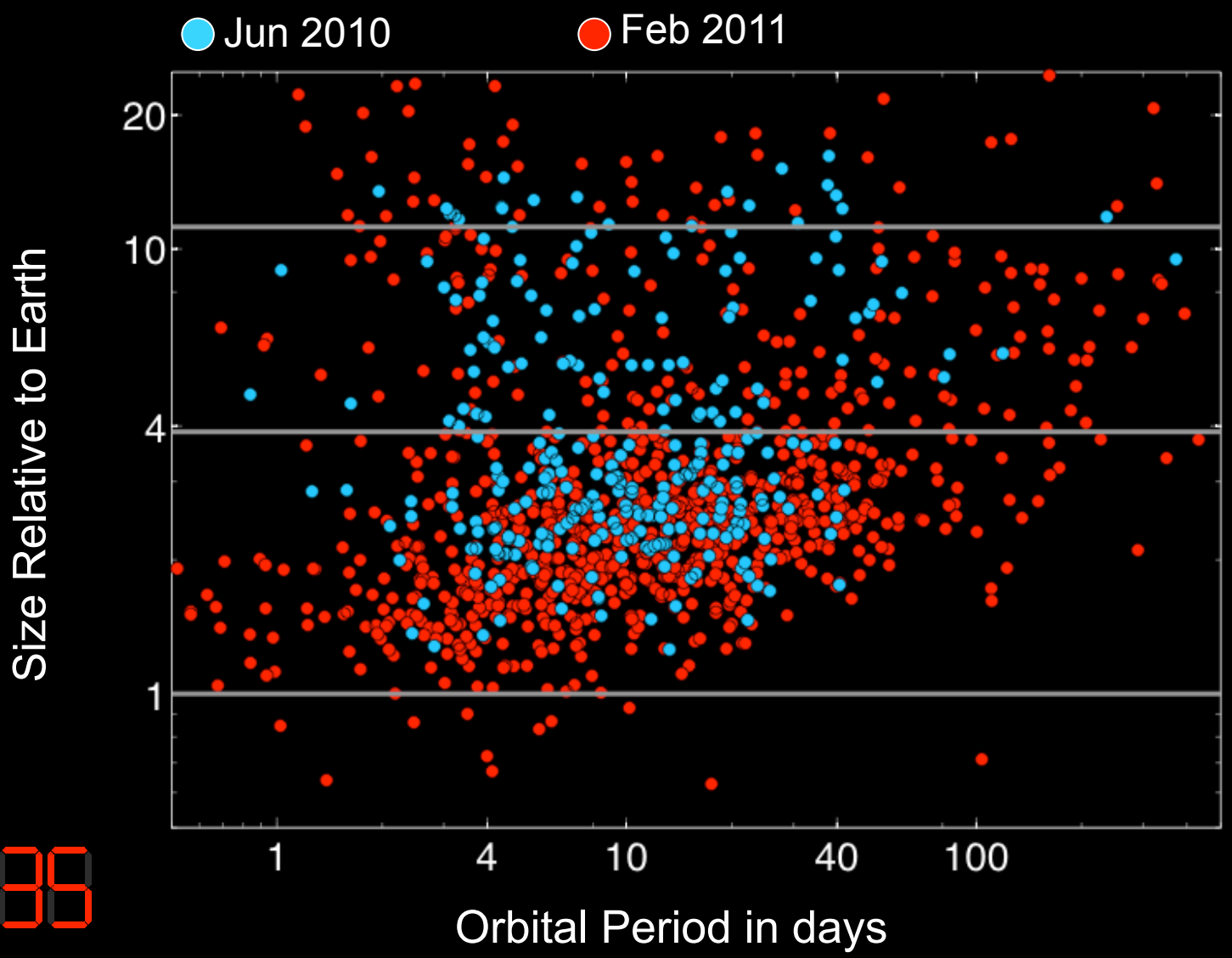
Candidates as of June 2010

Data: May-Sep 2009



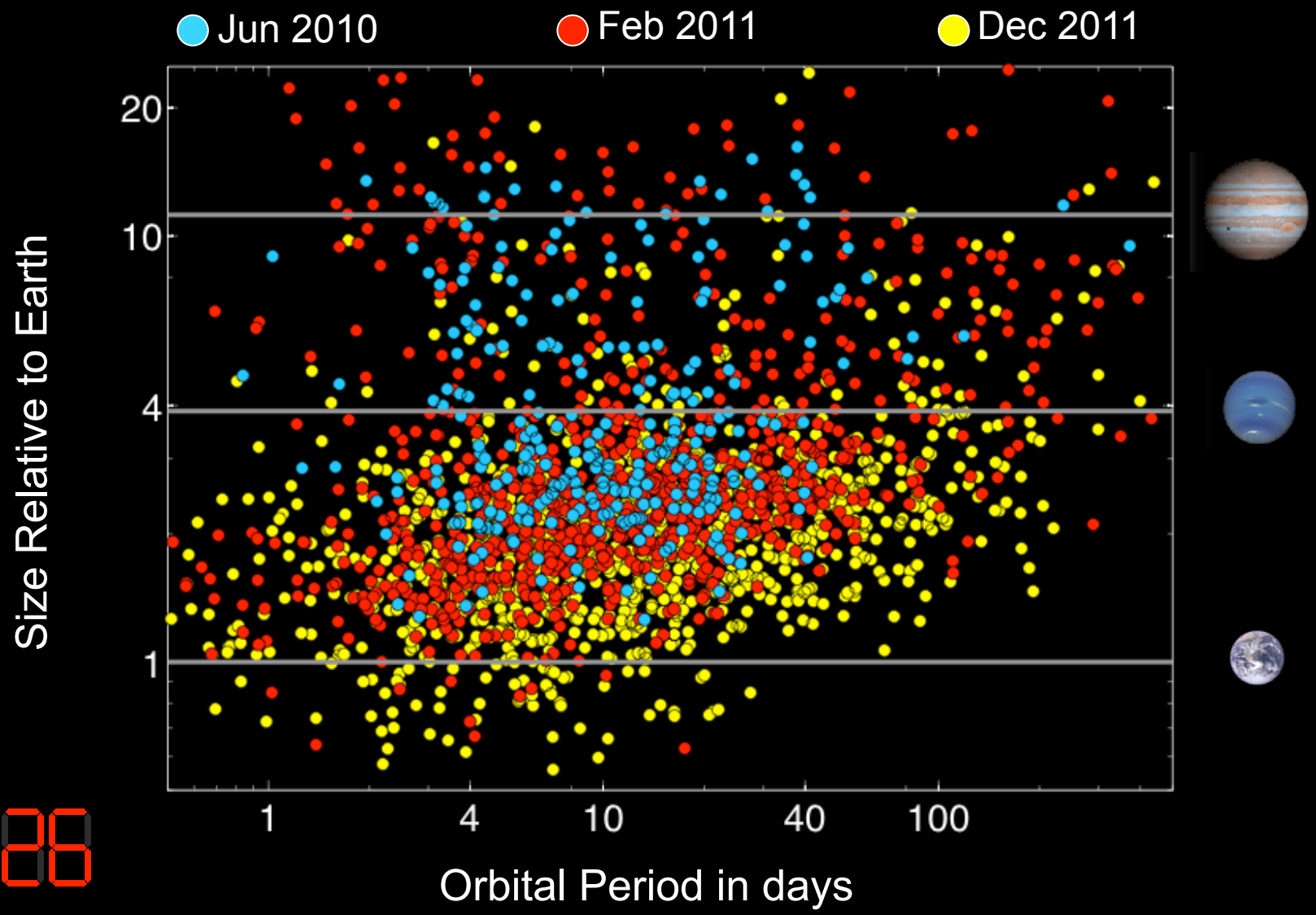
Candidates as of Feb 2011

Q0-Q5: May 2009 - Jun 2010



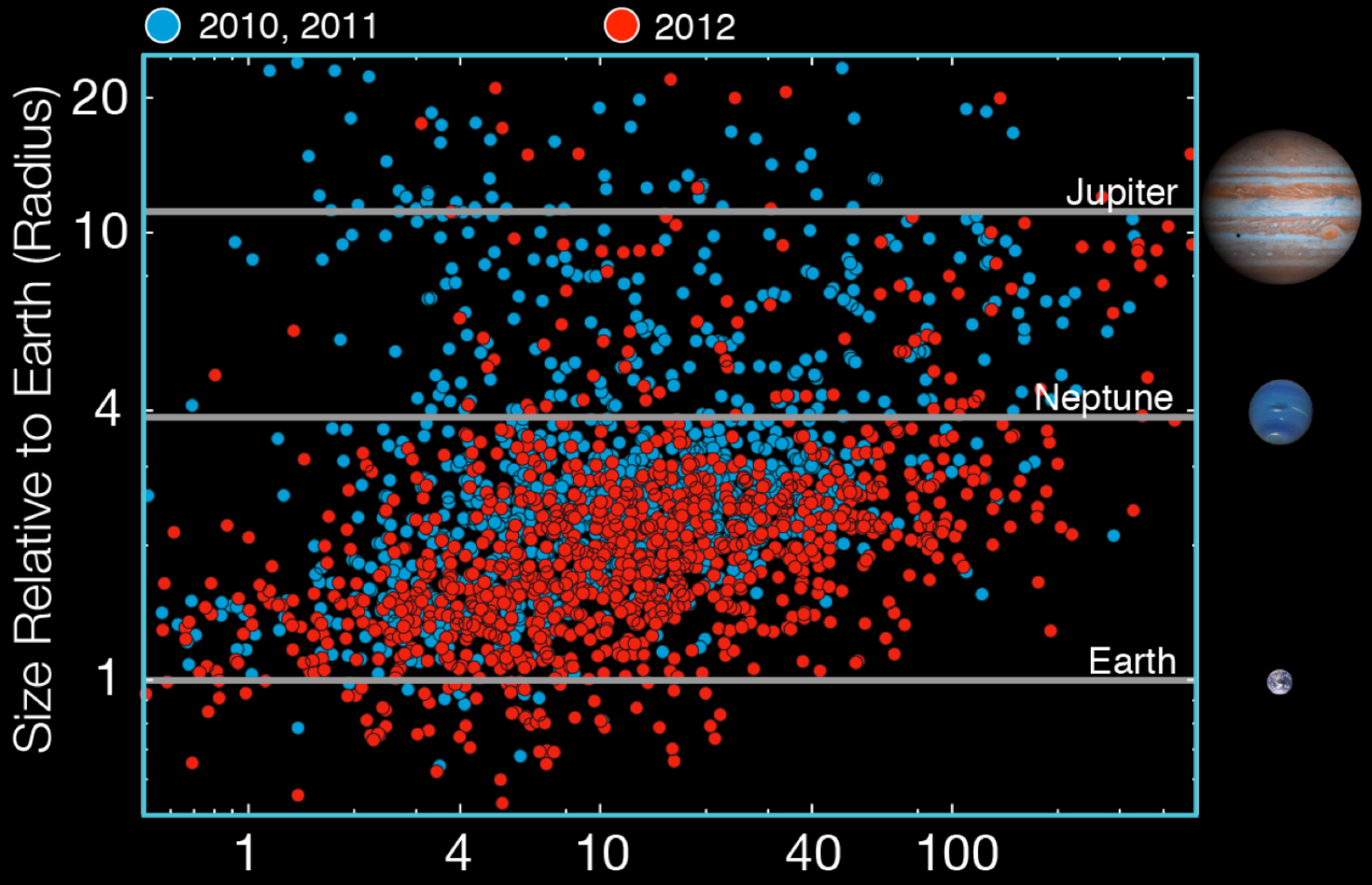
Candidates as of Dec 2011

Q0-Q6: May 2009 - Sep 2010



Planet Candidates

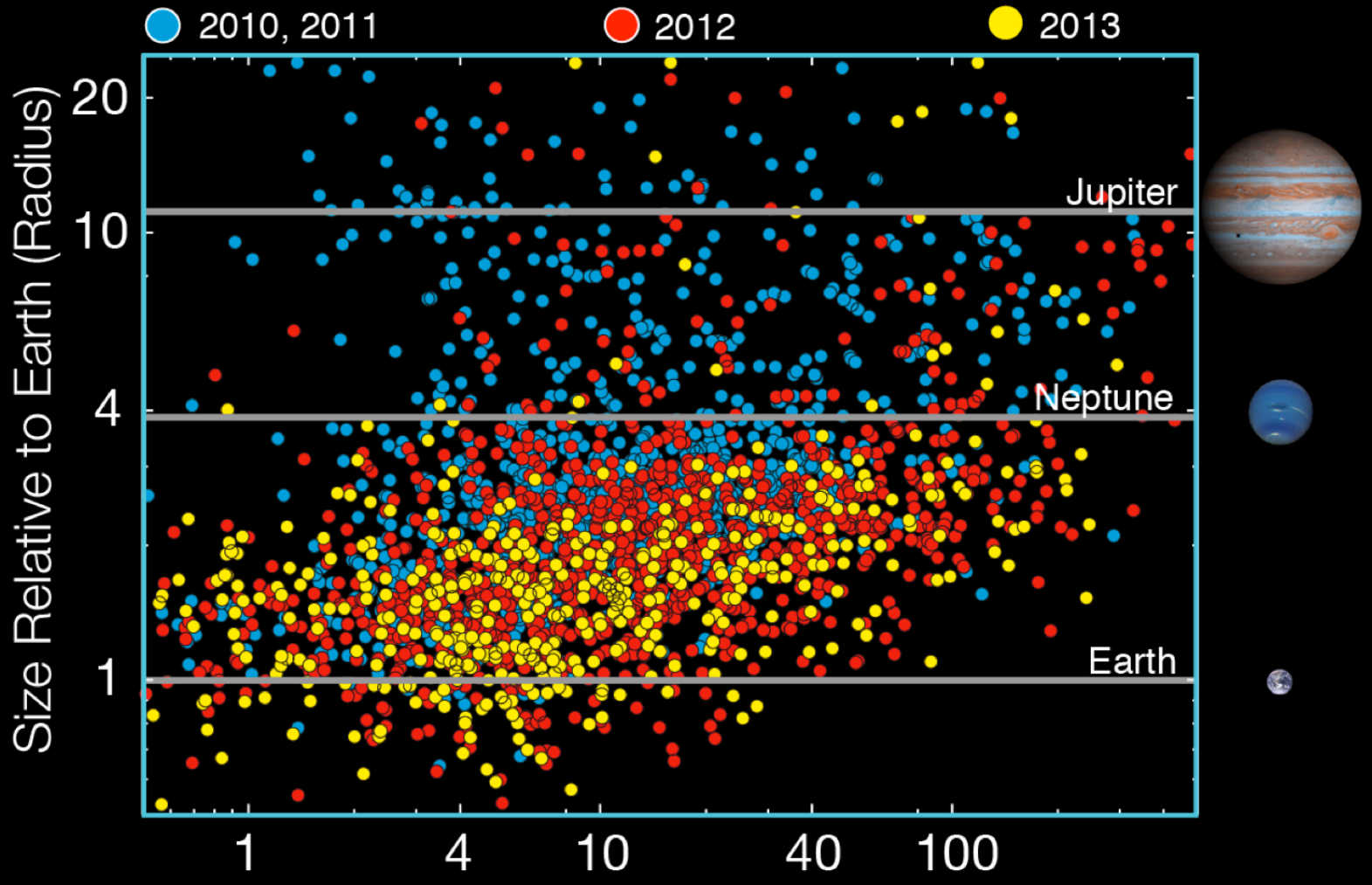
As of February 27, 2012



TOTAL = 2,321

Planet Candidates

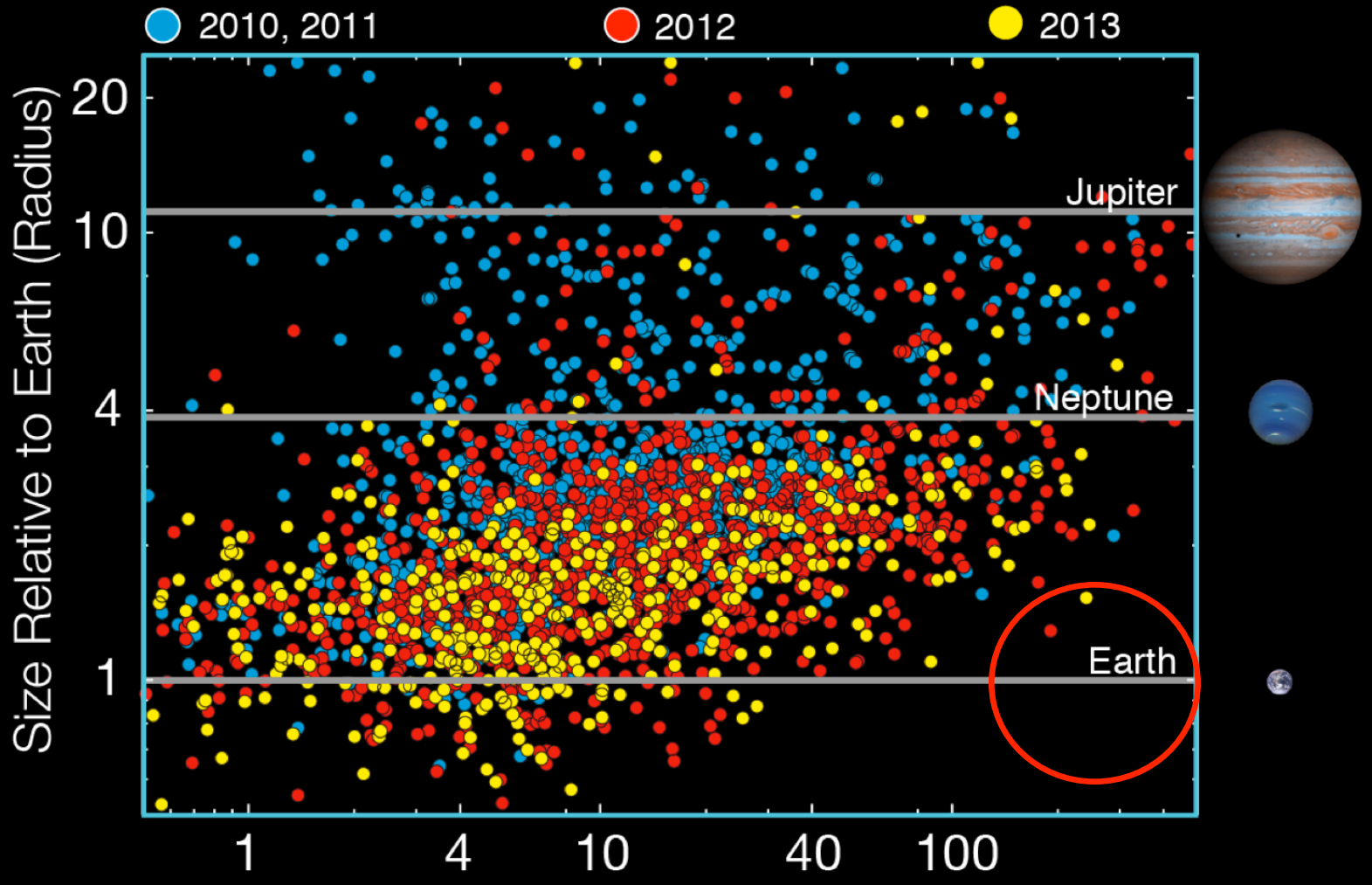
As of January 7, 2013



TOTAL = 2,740

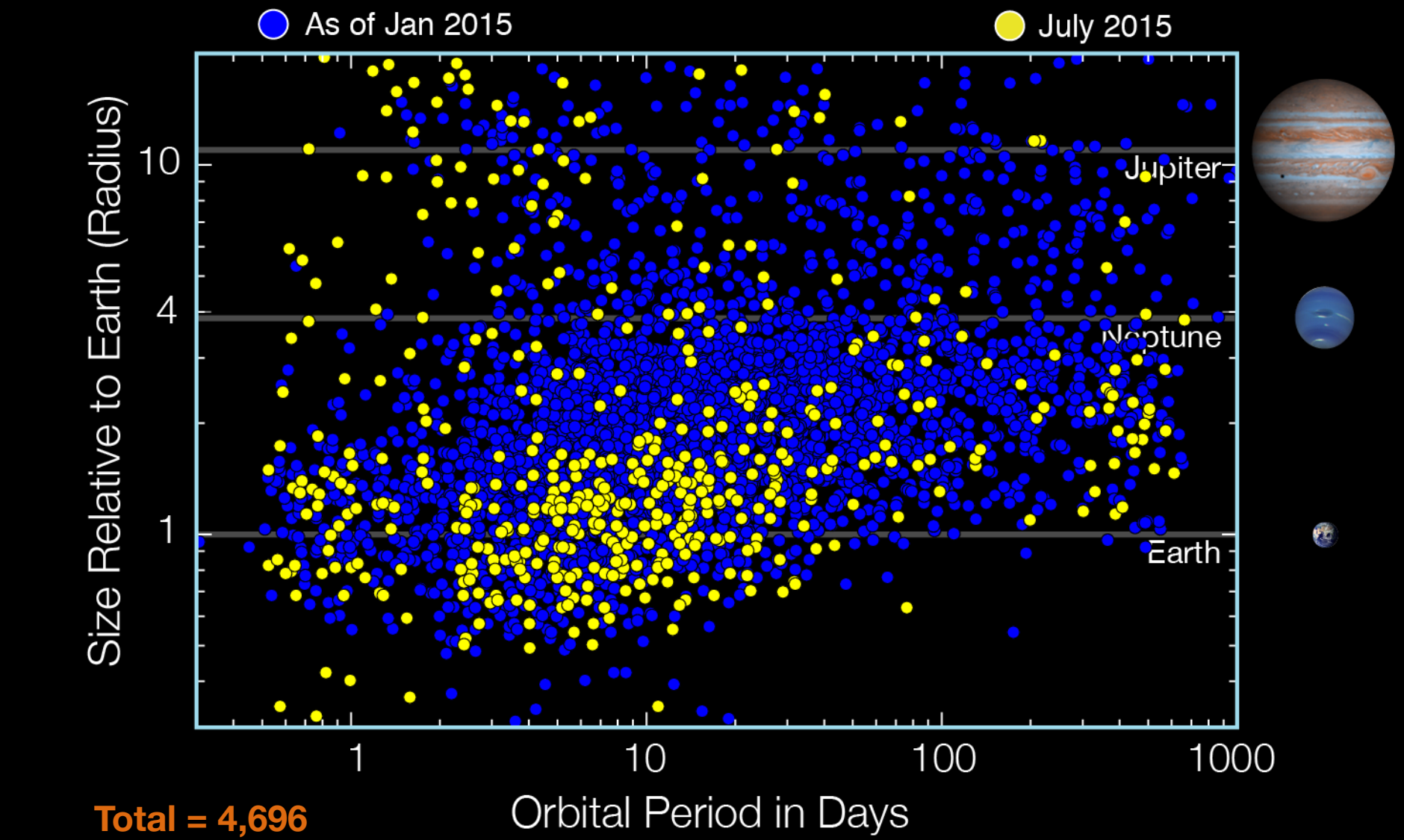
Planet Candidates

As of January 7, 2013



TOTAL = 2,740

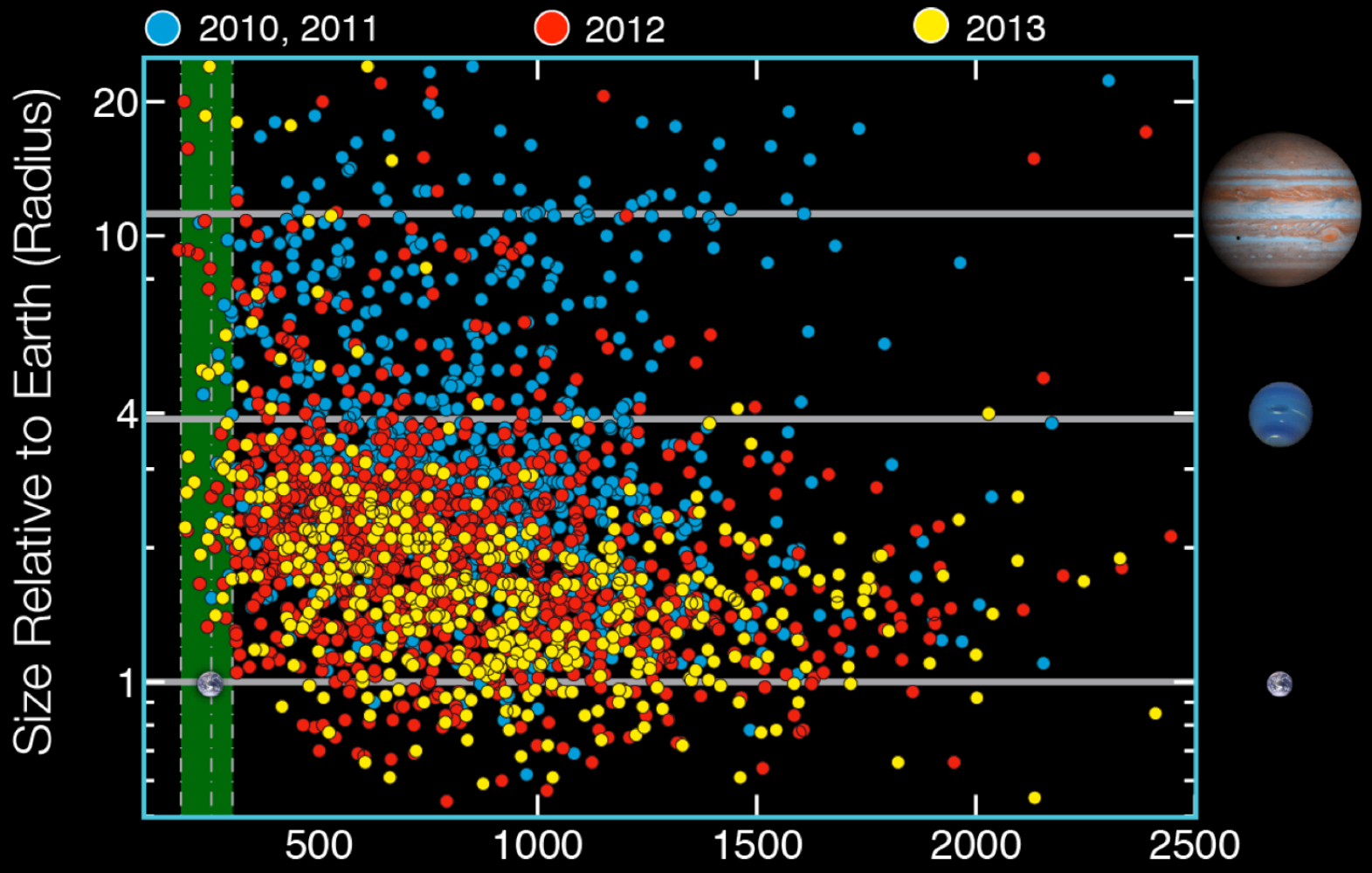
Kepler Planet Candidates



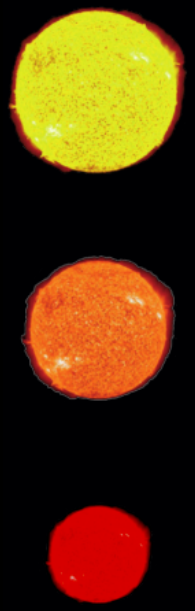
Total = 4,696

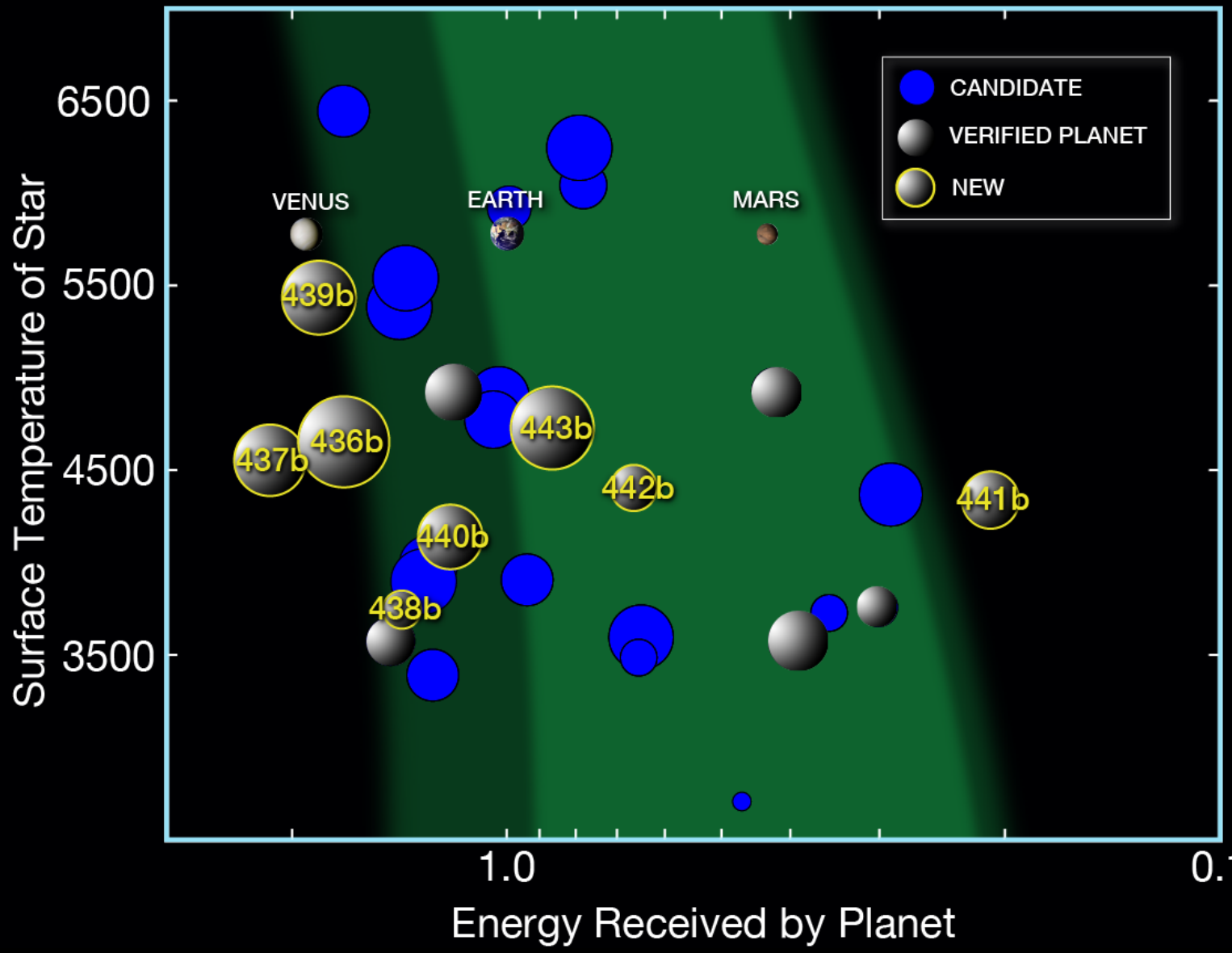
Candidates in the Habitable Zone

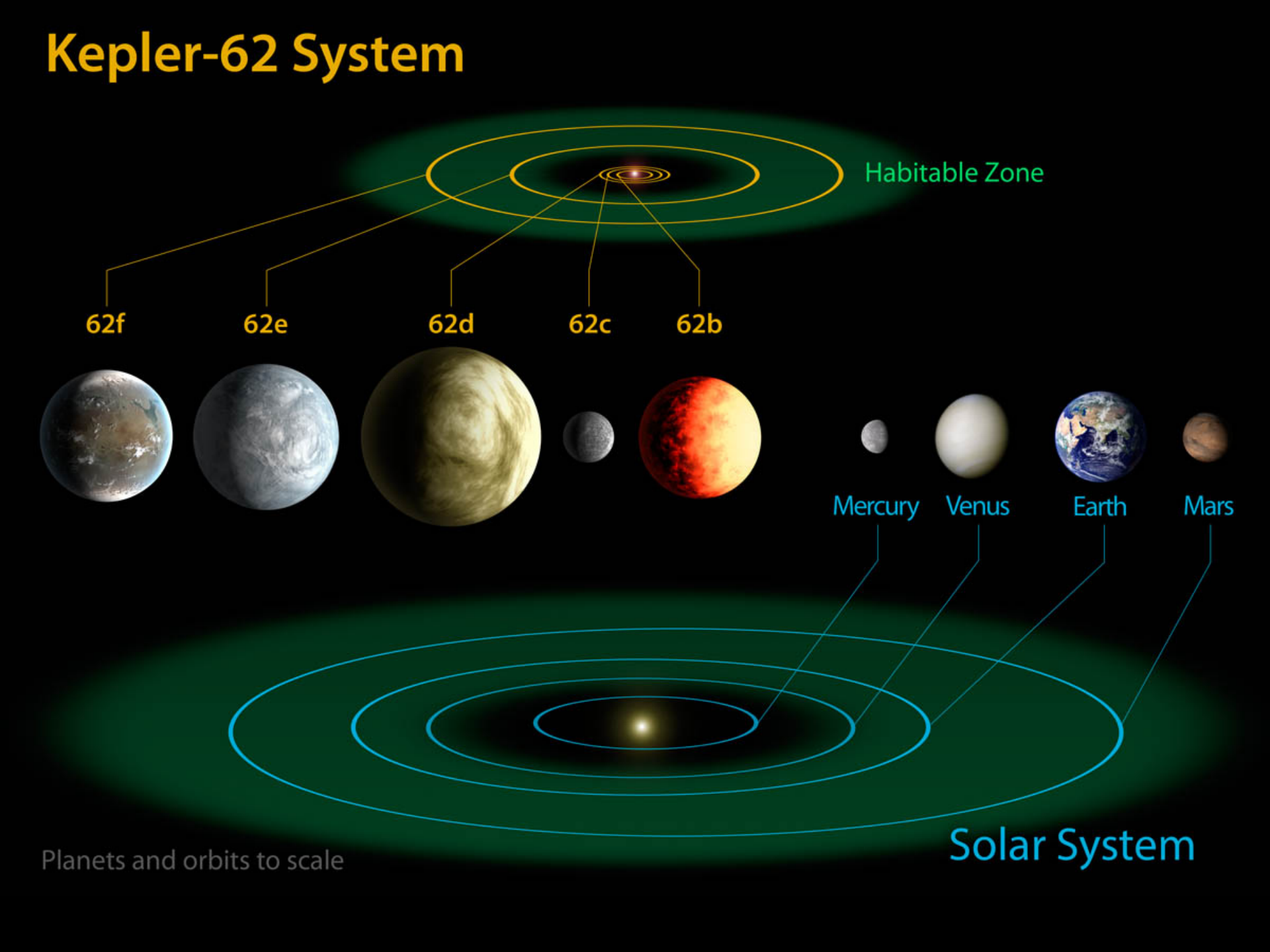
As of January 7, 2013

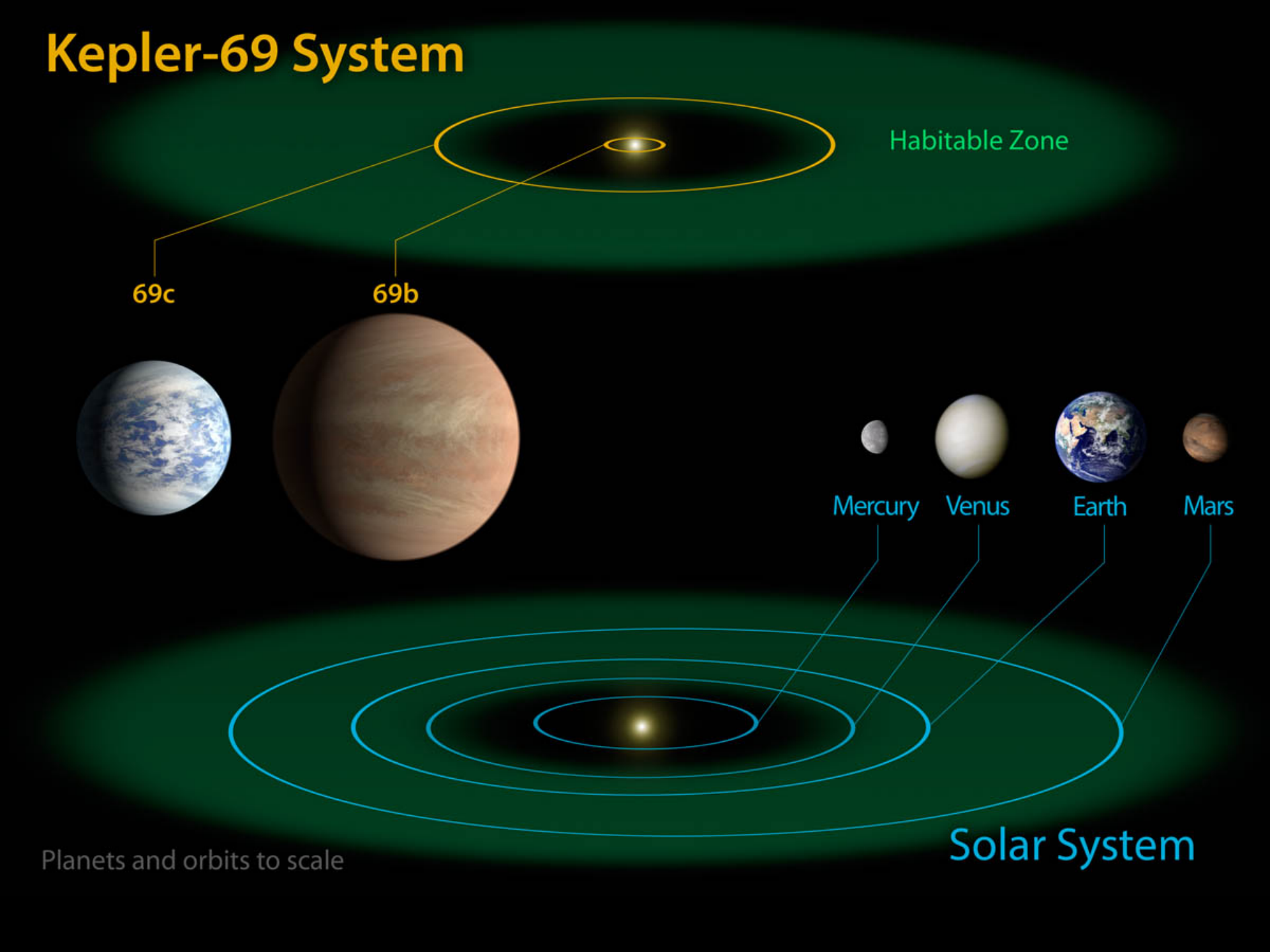


Habitable Zone Planets

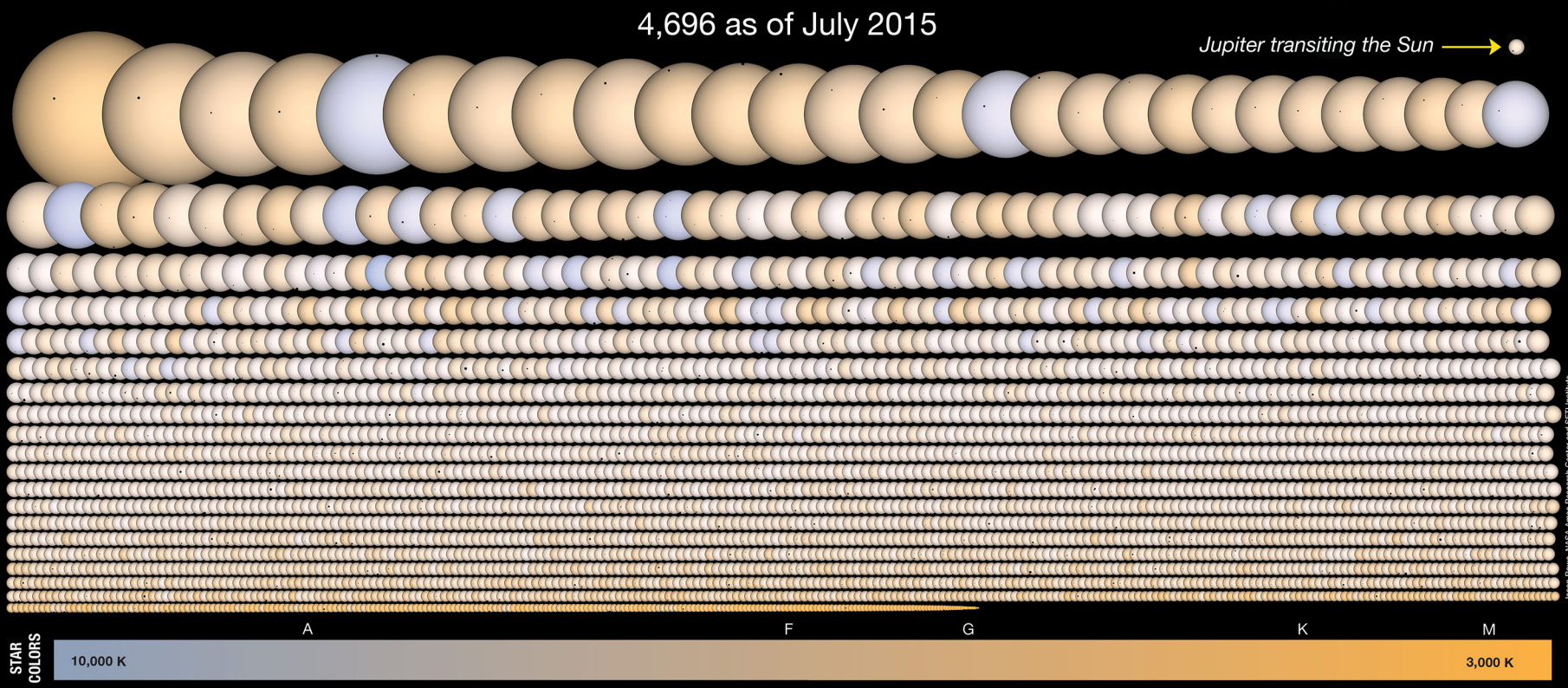




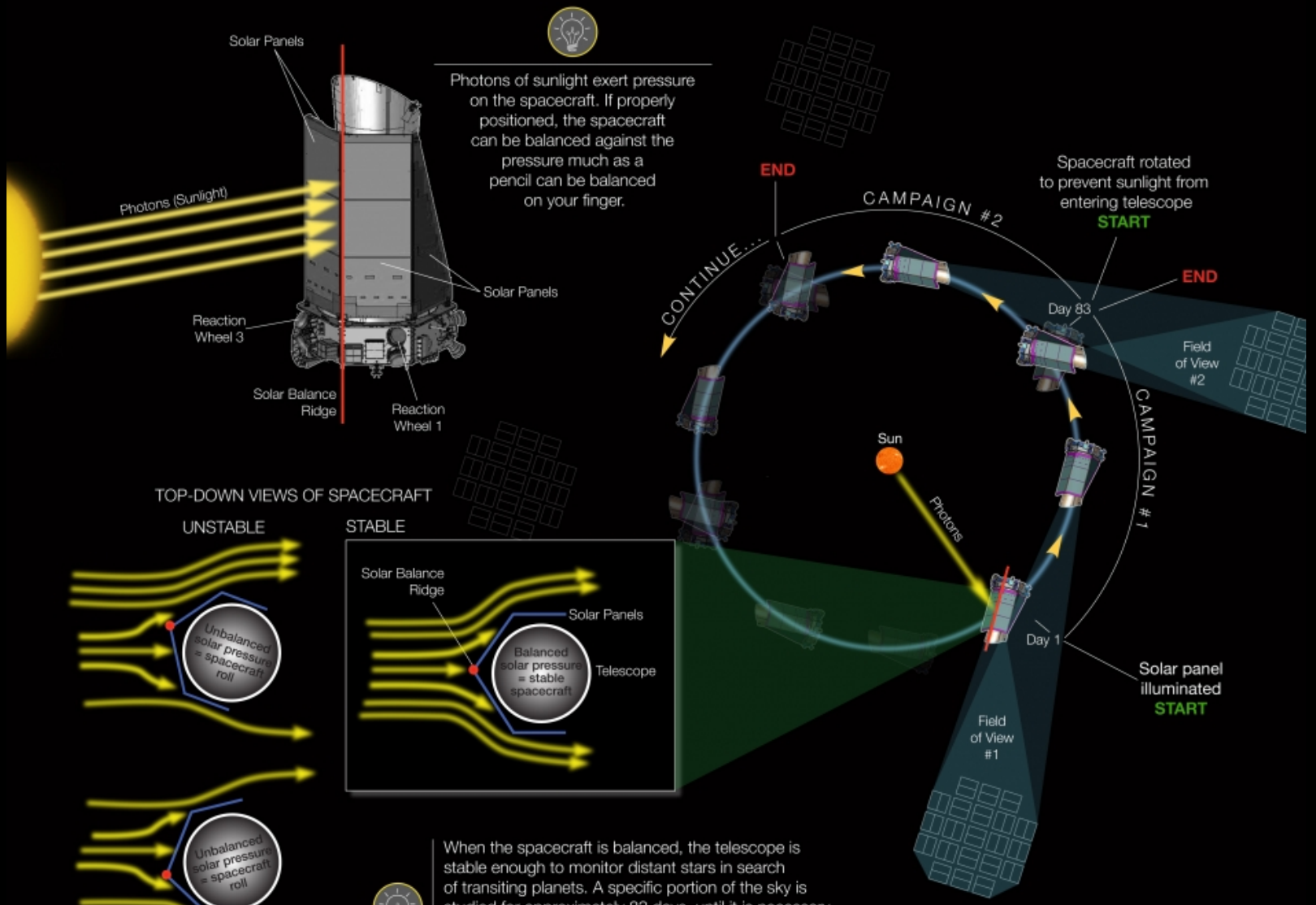

Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

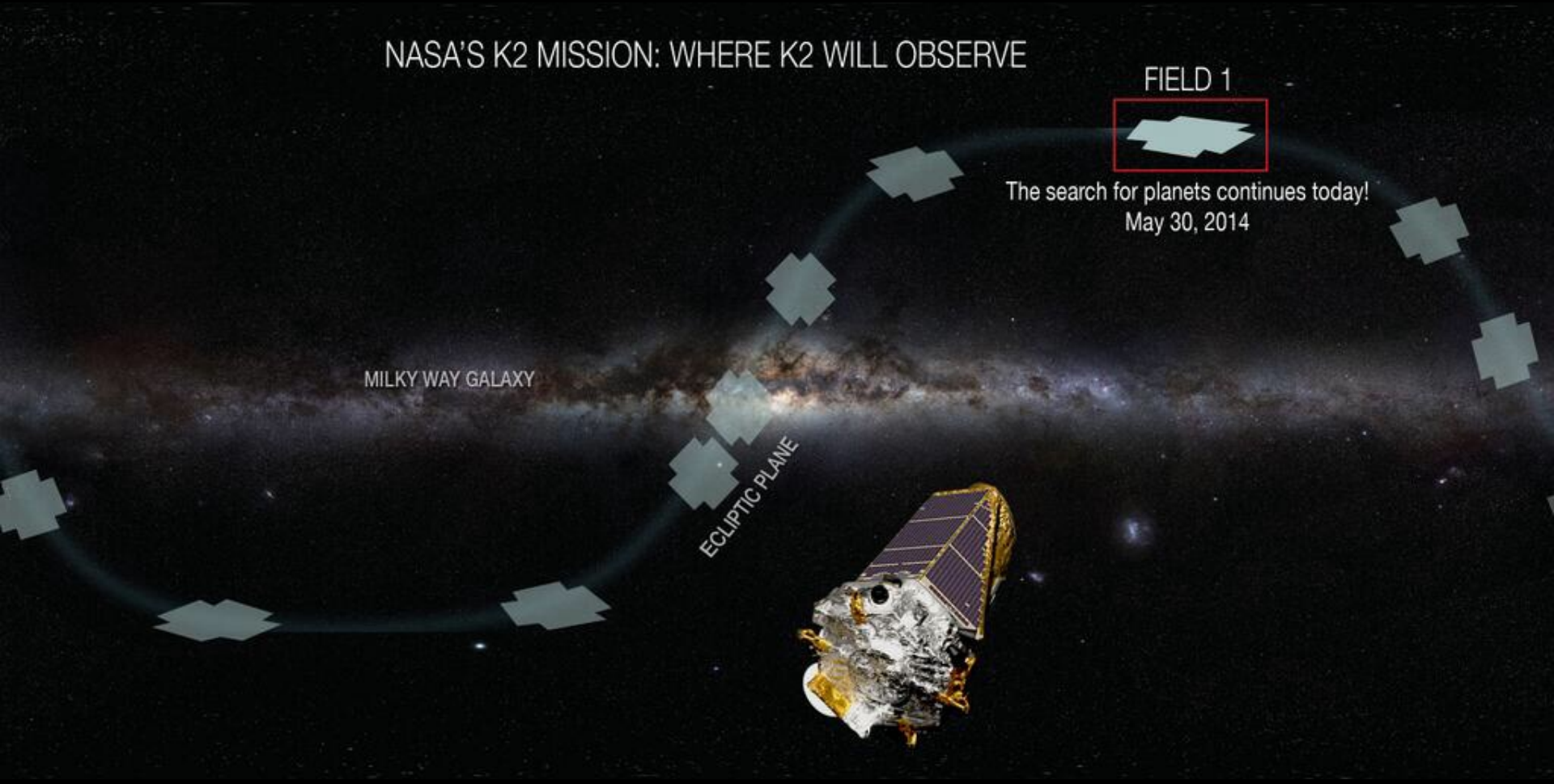

Kepler-69 System
Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

New Kepler Planet Candidates

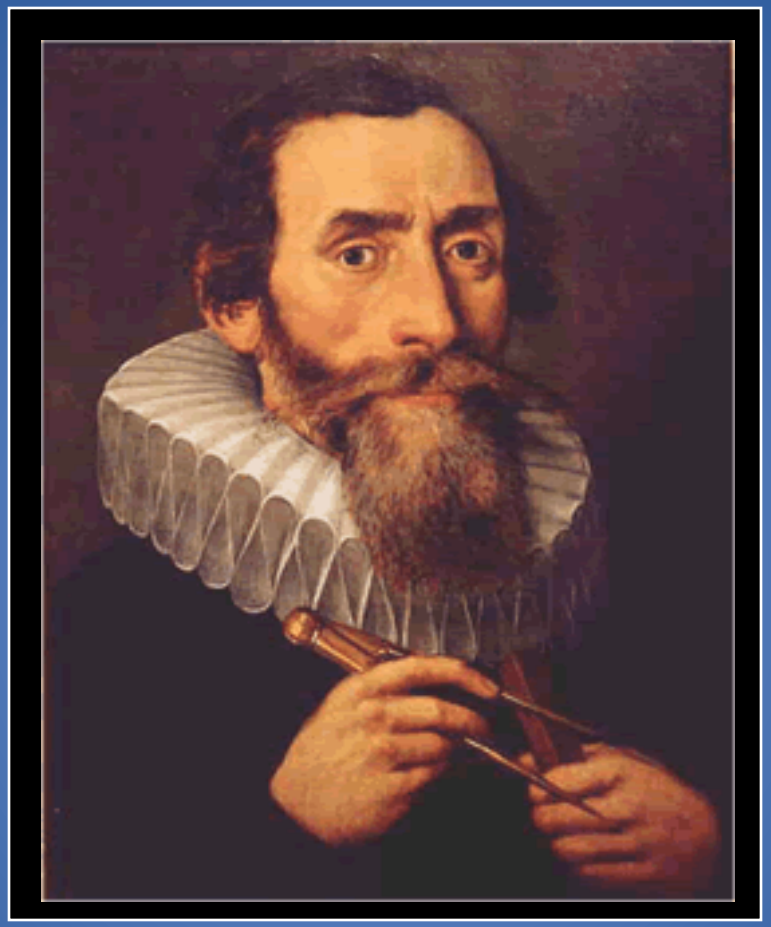


Kepler's Second Light: How K2 Will Work




NASA'S K2 MISSION: WHERE K2 WILL OBSERVE
FIELD 1
The search for planets continues today!
May 30, 2014
MILKY WAY GALAXY
ECLIPTIC PLANE


We seek
other worlds to better
understand our
place in the universe.



(By permission Sternwarte Kremsmünster)

A guy who's thought a lot about planets

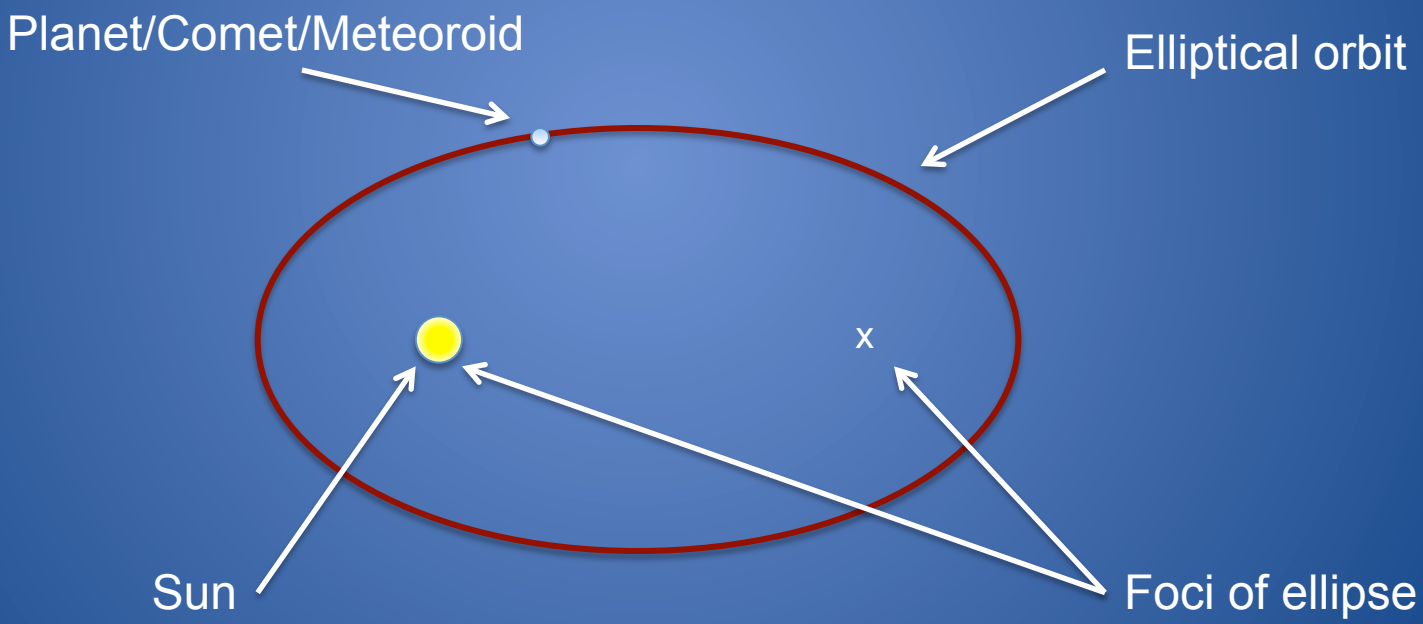
More information: kepler.nasa.gov

Kepler

A Search for Habitable Planets

Kepler's Laws of Planetary Motion

I. The orbit of every planet is an ellipse with the Sun at one of the two foci. (The other foci is empty.)



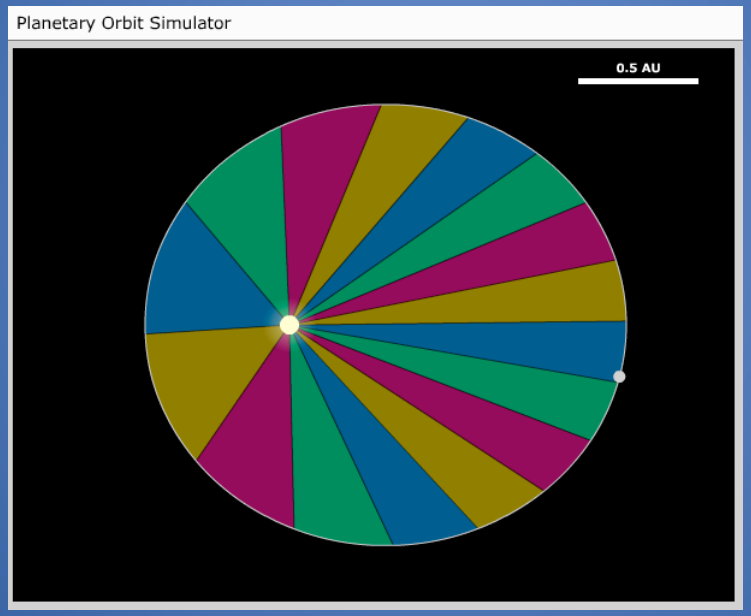
Note: This orbit is similar to the orbit of comets. Most planet's orbits would appear circular at this scale.

http://astro.unl.edu/classaction/animations/renaissance/kepler.html

A Search for Habitable Planets

Kepler's Laws of Planetary Motion

II.A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.



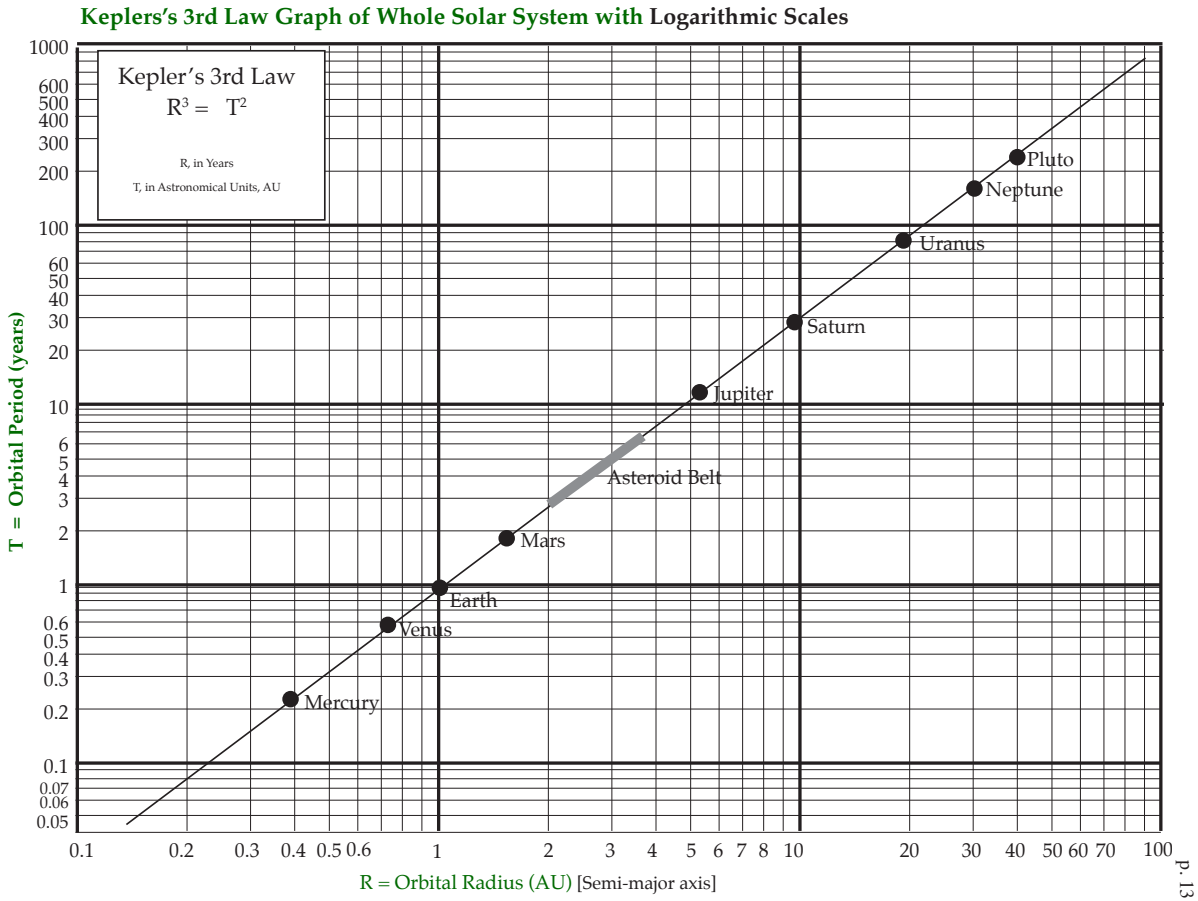
Orbit of Mercury marked in equal intervals of time using "Planetary Orbit Simulator."

http://astro.unl.edu/classaction/animations/renaissance/kepler.html

Kepler's Laws of Planetary Motion

A Search for Habitable Planets

III. The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.



Note: All objects -- planets, moons, asteroids, comets, meteoroids, dwarf planets -- all obey Kepler's 3rd Law.

Planet's Size: Deducing the Planet's Radius from Transit Data

A Search for Habitable Planets

$A_p/A_s = Z$

Converting to a percentage

$100\ (A_p/A_s) = Z\%$

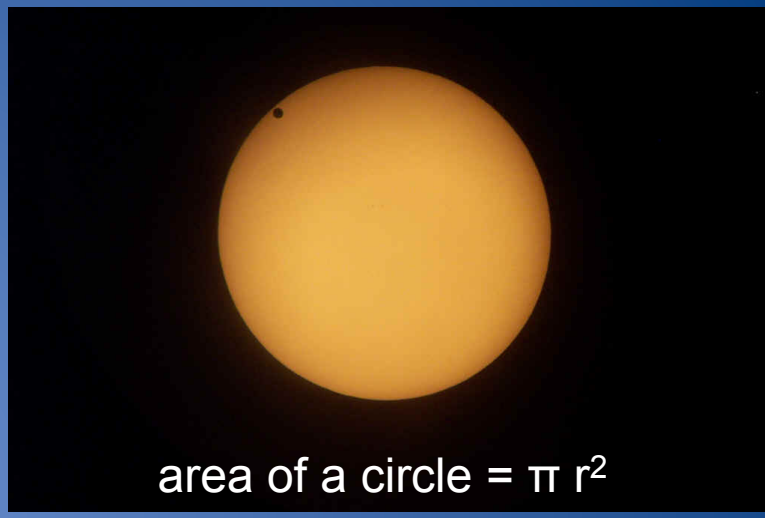
$100\ (\pi\ r_p^2 / \pi\ r_s^2) = Z\%$

$100\ (r_p^2 / r_s^2) = Z\%$

$r_p^2 / r_s^2 = Z\%/100$

$r_p^2 = r_s^2\ (Z\%/100)$

$r_p = r_s/10\ \sqrt{Z\%}$



The Sun is about 100 times the radius of the Earth.

$r_{sun} \sim 100\ r_{earth}$

Substituting:

$r_p = 100\ r_{earth}/10\ (\sqrt{Z\%}\ )$

$r_p = 10\ r_{earth}\ (\sqrt{Z\%}\ )$