Investigation: Transit Tracks

Students will learn

- what a transit is
- under what conditions a transit may be seen
- what effects a planet's size and distance from its star have on transit behavior
- how to interpret graphs of brightness vs time to deduce information about planet-star systems.

Materials and Preparation

- Clip-on lamp with frosted spherically shaped low wattage (25 W maximum) bulb.
- 4 beads, various sizes (3-12mm) and colors on strings of various lengths (20-100cm).
- Set of 5 graphs "Transit Light Curves" - one set per group of 2-5 students (master on p. 3).
- Blank paper and pencils pens (1 ea/student).
- Account of Jeremiah Horrocks observations of the transit of Venus from http://kepler.nasa.gov/ed/lc
- Optional: light sensor and computer with sensor interface and graphing function. Optional Distance/Size worksheets and Kepler's 3rd Law graph (masters on pp. 5–6).

A. What is a transit?

1. Introduce students to the concept of transits by reading a short account of the first transit observation by Jeremiah Horrocks (http://kepler.nasa.gov/ed/horrocks.html)

2. Demonstrate a transit by positioning the clip-on lamp at a height between standing eye-level and seated eye-level. Swing the largest bead on a string/thread in a circle around the lamp, with the lamp at the center in the plane of the orbit. Tell the class that the light bulb represents a star and the bead a planet; the planet is orbiting its star, like the Earth or Venus orbit the Sun.

   a. With students seated, ask if anyone can see the bead go directly in front of the star. If the lamp is high enough, none of the students will be able to see the bead go directly in front of the star.

   b. Ask students to move to where they can see the bead go directly in front of the star--it's OK to stand or crouch. After a show of hands indicates everyone can see that event, confirm that is what we mean by a transit—an event where one body goes in front of another, like a planet goes in front of a star.

B. How does a planet's size and orbit affect the transit?

To see how planet's diameter and orbit affect transits, orbit the other beads around the light. Make those with shorter strings go in smaller radius orbits with shorter period. Define "period" as the time for one orbit. Ask the students what's different about the planets. They should identify: size, color, period, distance from the star. Ask them if there is any relationship between the planet's period and how far it is from the light. They should notice that the farther it is from the light, the longer the period.

C. Interpreting Transit Graphs

1. Imagine a light sensor. Have students imagine they have a light sensor to measure the brightness of the star (light bulb). Move a large opaque object (e.g. a book or cardboard) in front of the star so that its light is completely blocked for all the students. Ask, "If we plotted a graph of brightness vs time—with brightness measured by our light sensor—and this [book] transited the star for 3 seconds, what would the graph look like?" Have volunteers come up and draw their ideas on the board and discuss with the class. We would expect the graph to look like the one shown in Fig. 1: a drop in brightness to 100% blocked.

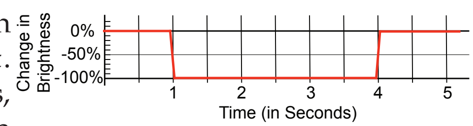


Figure 1. Light curve for a book passing in front of a light.

2. Graph for an orbiting planet. Ask the students, "What would a graph of sensor data look like for the orbiting planet, if we plotted brightness vs time?" Have volunteers draw their ideas on the board, and discuss with class. If their comments do not encompass the idea that the dips in brightness would be very narrow and that their depth would depend on the size of the beads/planets, ask them questions about how wide and deep the dips should be. We would expect the graph to look like the one shown in Fig. 2: horizontal line with dips in brightness to X% blocked.

3. What the graphs can tell us. Explain that with transit data, it's possible to calculate a planet's diameter and distance from its star. Ask, "Why do you think those two properties, planet diameter and distance from star, might be important?"

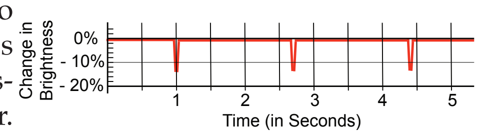


Figure 2. Light curve for a bead orbiting a light.

4. Analyze light curves. Hand out a set of 5 sample graphs of Transit Light Curves to each group of 2-5 students and have them interpret the graphs. Pose these questions: How big is the planet compared with the star? Assuming the star is Sun-like, and that Earth would make at 0.01% drop in brightness of the Sun if it transited, how big is the planet compared with Earth? What is/are the period(s) of the planet(s)? (In Earth years.) How far is the planet from its star? (Use graph of Kepler's 3rd Law) Lead a whole class discussion about the graphs, ultimately aiming at answering the questions.

D. Making Light Curves

1. Students create their own light curves, choosing planet size and orbit radius, and figuring out how to make the period for their graphs.

2. Trade light curves. They then trade graphs with other groups and challenge each other to figure out what kind of planet system they created.

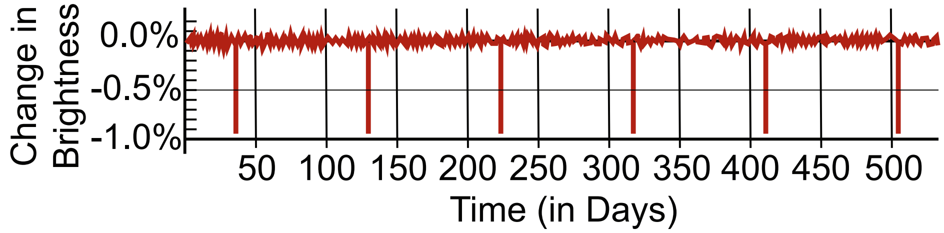
Optional: Collect Real Data

If you have a light sensor, computer with sensor interface, graphing software, and a computer display projector, place the light sensor in the plane of the planet/ bead orbit and aim sensor directly at the light. Collect brightness data and project the computer plot in real time. Let the students comment on what they are observing. Instead of swinging beads, you may use a mechanism, known as an orrery, to model the planets orbiting their star. Instructions for building an orrery from LEGO™ parts may be found on the NASA Kepler Mission website at http://kepler.nasa.gov/ed/lego.html.

Optional Transit Math.

Have the students compute planet size (from transit depth) and distance from its star (from transit period and Kepler's 3rd Law. See write-up for this at http://kepler.nasa.gov/ed/lc

A



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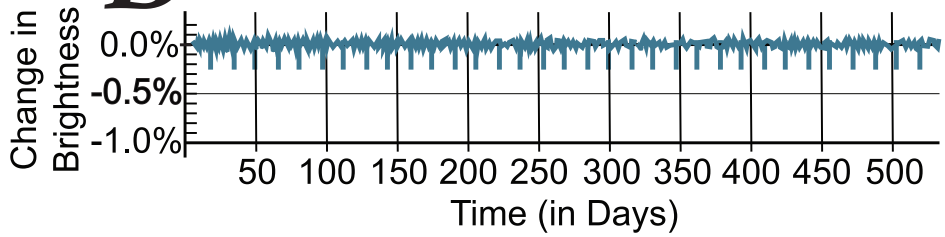

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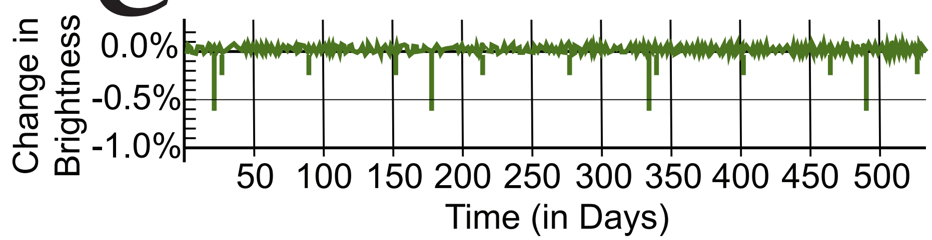

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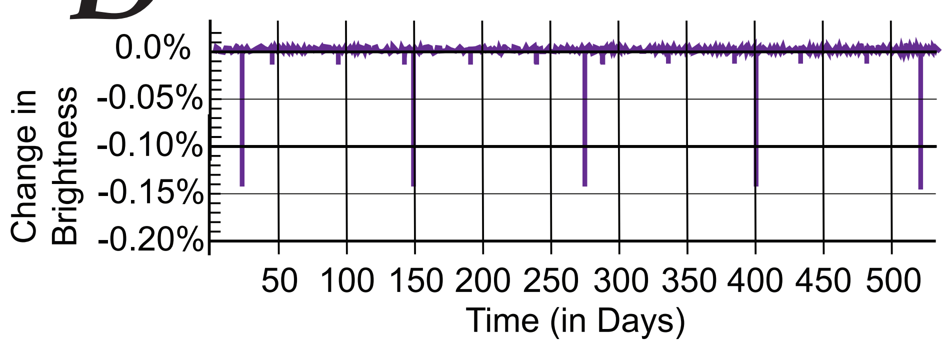

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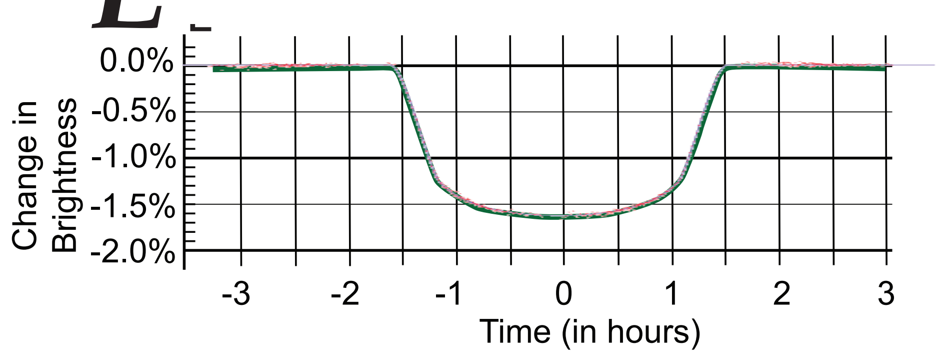
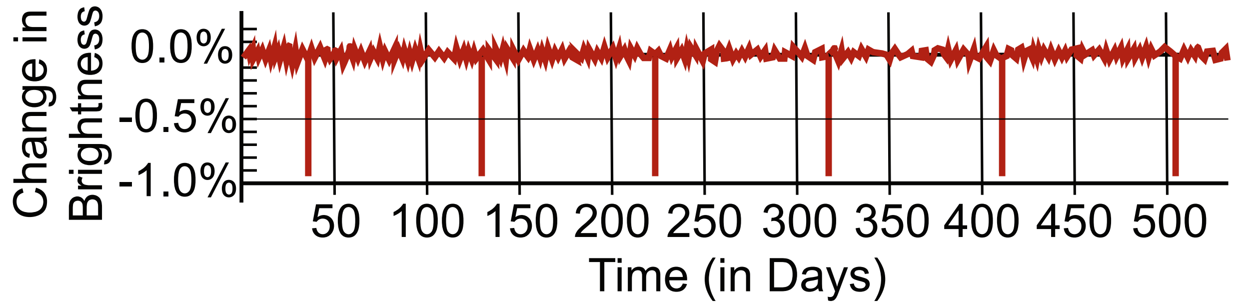


Transit Light Curves

for Tracking Transits Investigation

A



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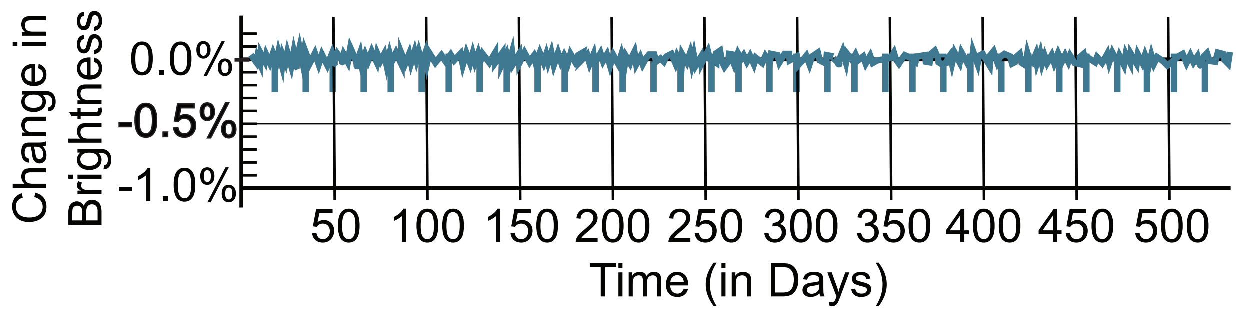

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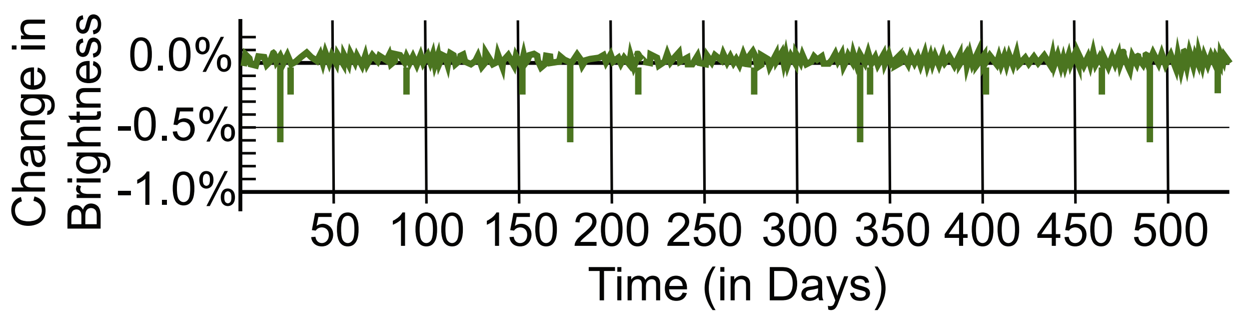

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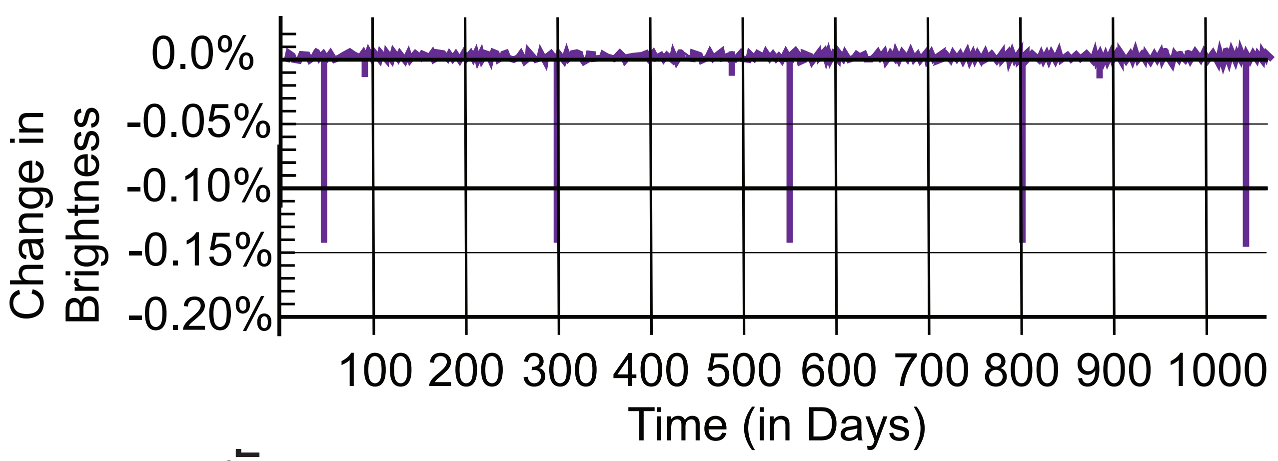

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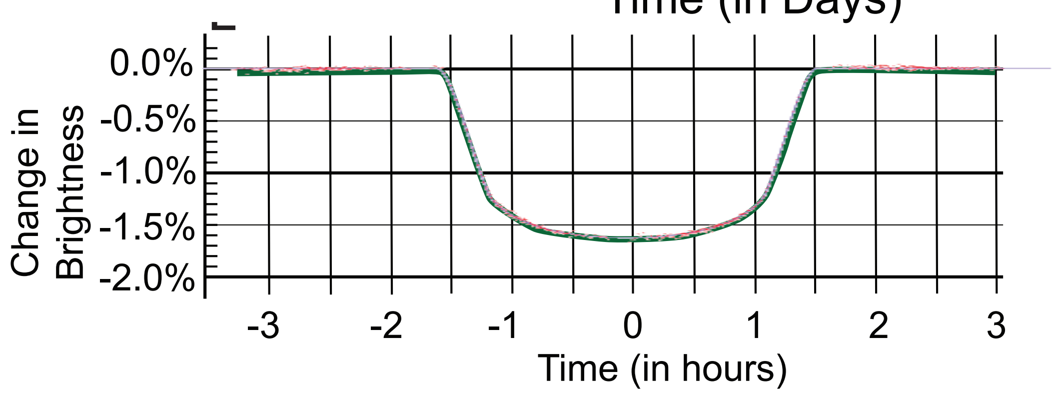


Optional Math for Transit Tracks

To introduce some math in the "Tracking Transits" investigation, have the students compute planet size and distance from its star.

PLANET DISTANCE FROM ITS STAR

The distance of the planet from the star is the radius (R) of its orbit, if the orbit is a circle with the star at the center. In reality, planet orbits are ellipses, but for simplicity, we can imagine the special case ellipse: a circle. Johannes Kepler found that a planet's orbit radius is related to its period (T), the time it takes to orbit. The farther out the planet is, the longer it takes to orbit. The relationship is known as Kepler's 3rd Law. Students can do the Kepler's 3rd law computation in one of two ways:

Method A-Graphical.

Use a graph of Kepler's 3rd Law: Orbital Radius (R) vs Orbital Period (T) on a logarithmic scale (master for photocopy on page 6). Logarithmic scale is needed to make adequate spacing in the inner solar system. Otherwise Mercury, Venus, Earth, and Mars would be so squeezed together, you could not distinguish them easily (see linear graph on page 10).

Method B-Computational.

Use formula for Kepler's 3rd Law: If we are dealing with a Sun-like star and express distance in AU (<u>A</u>stronomical <u>U</u>nit = average distance from Earth to the Sun), then Kepler's 3rd Law is simply:

$$R^3 = T^2 \quad *$$

or

$$R = \sqrt[3]{T^2}$$

* *Note: There is actually a constant K implied in this equation that sets the units straight:*

$R^3/T^2 = K$ *where* $K = 1\ AU^3/Year^2$

Students can use a worksheet to make this computation simple with easy steps. Master for photocopy is on page 6.

It's a good idea to do an example and give some for exercise:

T = 1 yr, 2.83 yr, 5.196 yr, 0.3535 yr
R = 1 AU, 2 AU, 3 AU, 1/2 AU

PLANET SIZE

If we call the percent drop in brightness on a light curve graph Z%, and if the star is about the size of the Sun, then the radius of the planet (r_p) as compared with the radius of Earth (r_e) is

$$r_p = 10\ r_e \times \sqrt{Z}$$

Do an example and the give some examples to students as exercises: Z = 25%, 49%, 9%, 16%, 4%

For Z= 25%, r_p = 50 Earth radii

Note if Z=49%, it's probably not a planet at all, but a companion star in a binary star system.

For more "hot shot" students that get done fast, challenge them to derive the formula using algebra. Have them start with the basic idea that drop in brightness is the ratio of the area of the planet (A_p) to the area of the star (A_s):

$$A_p / A_s \times 100 = Z\%$$

They can use the formula for Area

$$A = \pi r^2$$

Here are the steps:

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

or $r_p = r_s \times \sqrt{(Z/100)} = r_s \times \sqrt{(Z)}/10$

where r_s is the radius of the star.

If the star is about the size of the Sun, then the radius of the star is about 100 times the radius of Earth (r_E) and

$$r_p = 10 r_E \times \sqrt{Z} \quad \text{(QED)}$$

Two ways to take the cube root of a number:

I. Cube Root table on pp 7–9, based on table at http://www.geocities.com/longhairedbastard/appendix3.htm

II. On a calculator that has ln or log function,

1. Enter X,
2. press the "ln" (or "log") key,
3. divide by 3,
4. then press "e^x" (or 10^x) key

And you now have the cube root of X.

Note the "e^x" key may require using the "inv" key on your calculator, depending how your function keys are laid out.

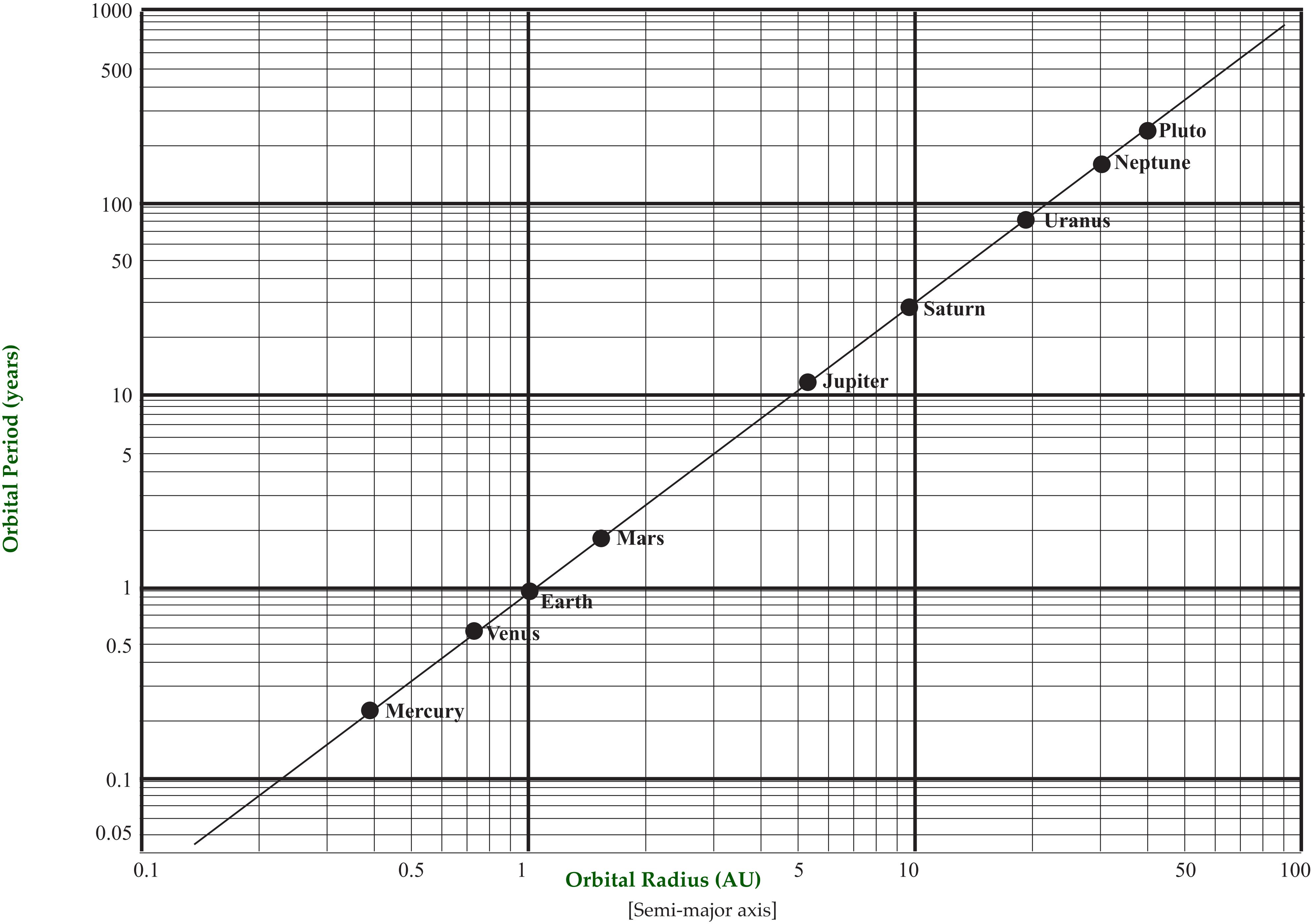
Planet Distance Worksheet

Star/Planet	Period (T)	T^2	Distance (orbit radius) $\sqrt[3]{T^2}$

Planet Size Worksheet

Star/Planet	Z (%)	$\sqrt{Z}$	Size (in Earth radii) $10 \times \sqrt{Z}$

Keplers's 3rd Law

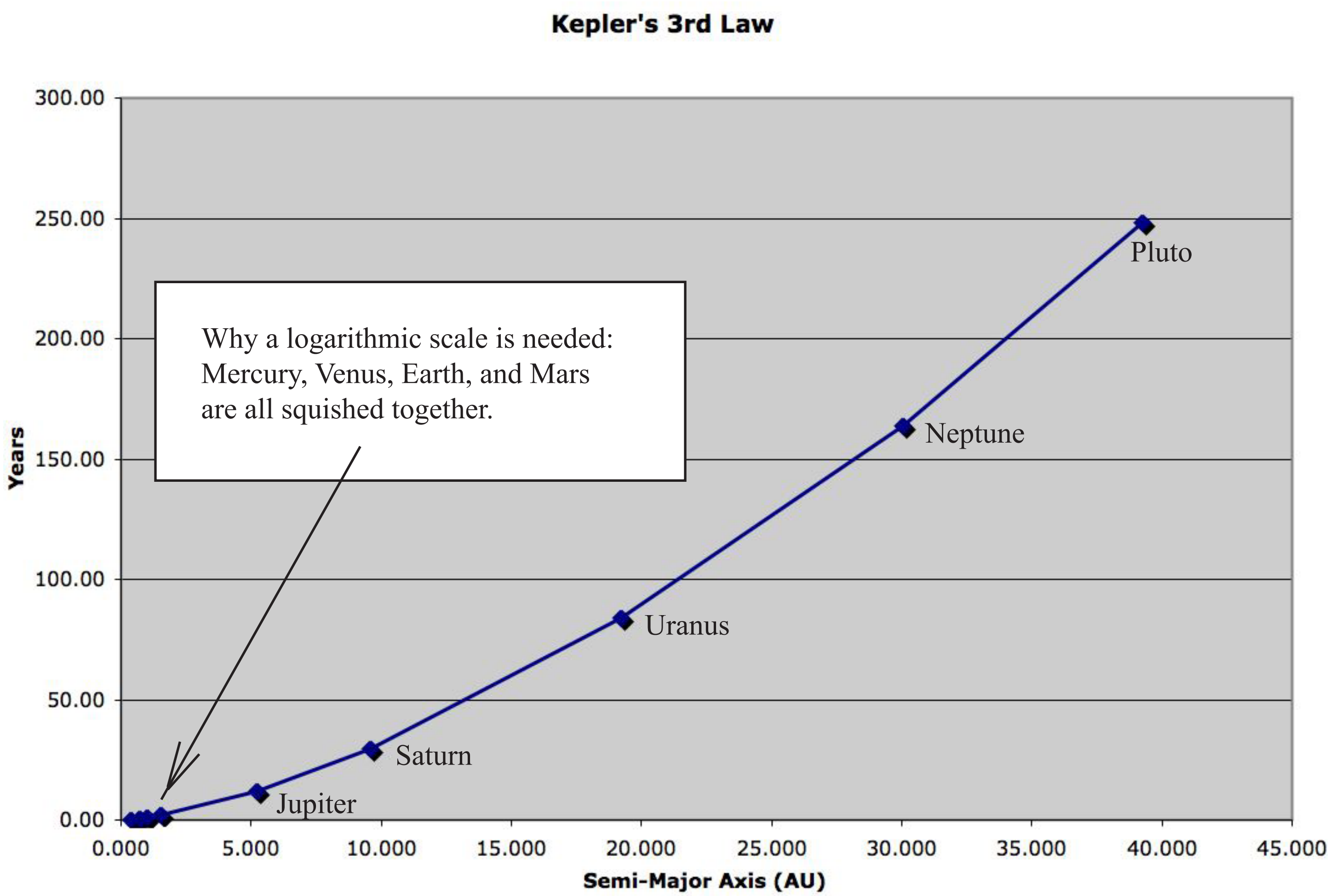


#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root
1	1	51	3.708	101	4.657	151	5.325	201	5.858	251	6.308	301	6.702	351	7.054
2	1.260	52	3.733	102	4.672	152	5.337	202	5.867	252	6.316	302	6.709	352	7.061
3	1.442	53	3.756	103	4.688	153	5.348	203	5.877	253	6.325	303	6.717	353	7.067
4	1.587	54	3.780	104	4.703	154	5.360	204	5.887	254	6.333	304	6.724	354	7.074
5	1.710	55	3.803	105	4.718	155	5.372	205	5.896	255	6.341	305	6.731	355	7.081
6	1.817	56	3.826	106	4.733	156	5.383	206	5.906	256	6.350	306	6.739	356	7.087
7	1.913	57	3.849	107	4.747	157	5.395	207	5.915	257	6.358	307	6.746	357	7.094
8	2	58	3.871	108	4.762	158	5.406	208	5.925	258	6.366	308	6.753	358	7.101
9	2.080	59	3.893	109	4.777	159	5.418	209	5.934	259	6.374	309	6.761	359	7.107
10	2.154	60	3.915	110	4.791	160	5.429	210	5.944	260	6.383	310	6.768	360	7.114
11	2.224	61	3.936	111	4.806	161	5.440	211	5.953	261	6.391	311	6.775	361	7.120
12	2.289	62	3.958	112	4.820	162	5.451	212	5.963	262	6.399	312	6.782	362	7.127
13	2.351	63	3.979	113	4.835	163	5.463	213	5.972	263	6.407	313	6.790	363	7.133
14	2.410	64	4	114	4.849	164	5.474	214	5.981	264	6.415	314	6.797	364	7.140
15	2.466	65	4.021	115	4.863	165	5.485	215	5.991	265	6.423	315	6.804	365	7.147
16	2.520	66	4.041	116	4.877	166	5.496	216	6	266	6.431	316	6.811	366	7.153
17	2.571	67	4.062	117	4.891	167	5.507	217	6.009	267	6.439	317	6.818	367	7.160
18	2.621	68	4.082	118	4.905	168	5.518	218	6.018	268	6.447	318	6.826	368	7.166
19	2.668	69	4.102	119	4.919	169	5.529	219	6.028	269	6.455	319	6.833	369	7.173
20	2.714	70	4.121	120	4.932	170	5.540	220	6.037	270	6.463	320	6.840	370	7.179
21	2.759	71	4.141	121	4.946	171	5.550	221	6.046	271	6.471	321	6.847	371	7.186
22	2.802	72	4.160	122	4.960	172	5.561	222	6.055	272	6.479	322	6.854	372	7.192
23	2.844	73	4.179	123	4.973	173	5.572	223	6.064	273	6.487	323	6.861	373	7.198
24	2.884	74	4.198	124	4.987	174	5.583	224	6.073	274	6.495	324	6.868	374	7.205
25	2.924	75	4.217	125	5	175	5.593	225	6.082	275	6.503	325	6.875	375	7.211
26	2.962	76	4.236	126	5.013	176	5.604	226	6.091	276	6.511	326	6.882	376	7.218
27	3	77	4.254	127	5.027	177	5.615	227	6.100	277	6.519	327	6.889	377	7.224
28	3.037	78	4.273	128	5.040	178	5.625	228	6.109	278	6.527	328	6.896	378	7.230
29	3.072	79	4.291	129	5.053	179	5.636	229	6.118	279	6.534	329	6.903	379	7.237
30	3.107	80	4.309	130	5.066	180	5.646	230	6.127	280	6.542	330	6.910	380	7.243
31	3.141	81	4.327	131	5.079	181	5.657	231	6.136	281	6.550	331	6.917	381	7.250
32	3.175	82	4.344	132	5.092	182	5.667	232	6.145	282	6.558	332	6.924	382	7.256
33	3.208	83	4.362	133	5.104	183	5.677	233	6.153	283	6.565	333	6.931	383	7.262
34	3.240	84	4.380	134	5.117	184	5.688	234	6.162	284	6.573	334	6.938	384	7.268
35	3.271	85	4.397	135	5.130	185	5.698	235	6.171	285	6.581	335	6.945	385	7.275
36	3.302	86	4.414	136	5.143	186	5.708	236	6.180	286	6.589	336	6.952	386	7.281
37	3.332	87	4.431	137	5.155	187	5.718	237	6.188	287	6.596	337	6.959	387	7.287
38	3.362	88	4.448	138	5.168	188	5.729	238	6.197	288	6.604	338	6.966	388	7.294
39	3.391	89	4.465	139	5.180	189	5.739	239	6.206	289	6.611	339	6.973	389	7.300
40	3.420	90	4.481	140	5.192	190	5.749	240	6.214	290	6.619	340	6.980	390	7.306
41	3.448	91	4.498	141	5.205	191	5.759	241	6.223	291	6.627	341	6.986	391	7.312
42	3.476	92	4.514	142	5.217	192	5.769	242	6.232	292	6.634	342	6.993	392	7.319
43	3.503	93	4.531	143	5.229	193	5.779	243	6.240	293	6.642	343	7	393	7.325
44	3.530	94	4.547	144	5.241	194	5.789	244	6.249	294	6.649	344	7.007	394	7.331
45	3.557	95	4.563	145	5.254	195	5.799	245	6.257	295	6.657	345	7.014	395	7.337
46	3.583	96	4.579	146	5.266	196	5.809	246	6.266	296	6.664	346	7.020	396	7.343
47	3.609	97	4.595	147	5.278	197	5.819	247	6.274	297	6.672	347	7.027	397	7.350
48	3.634	98	4.610	148	5.290	198	5.828	248	6.283	298	6.679	348	7.034	398	7.356
49	3.659	99	4.626	149	5.301	199	5.838	249	6.291	299	6.687	349	7.041	399	7.362
50	3.684	100	4.642	150	5.313	200	5.848	250	6.300	300	6.694	350	7.047	400	7.368

#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root
401	7.374	451	7.669	501	7.942	551	8.198	601	8.439	651	8.667	701	8.883	751	9.090
402	7.380	452	7.674	502	7.948	552	8.203	602	8.444	652	8.671	702	8.887	752	9.094
403	7.386	453	7.680	503	7.953	553	8.208	603	8.448	653	8.676	703	8.892	753	9.098
404	7.393	454	7.686	504	7.958	554	8.213	604	8.453	654	8.680	704	8.896	754	9.102
405	7.399	455	7.691	505	7.963	555	8.218	605	8.458	655	8.685	705	8.900	755	9.106
406	7.405	456	7.697	506	7.969	556	8.223	606	8.462	656	8.689	706	8.904	756	9.110
407	7.411	457	7.703	507	7.974	557	8.228	607	8.467	657	8.693	707	8.909	757	9.114
408	7.417	458	7.708	508	7.979	558	8.233	608	8.472	658	8.698	708	8.913	758	9.118
409	7.423	459	7.714	509	7.984	559	8.238	609	8.476	659	8.702	709	8.917	759	9.122
410	7.429	460	7.719	510	7.990	560	8.243	610	8.481	660	8.707	710	8.921	760	9.126
411	7.435	461	7.725	511	7.995	561	8.247	611	8.486	661	8.711	711	8.925	761	9.130
412	7.441	462	7.731	512	8	562	8.252	612	8.490	662	8.715	712	8.929	762	9.134
413	7.447	463	7.736	513	8.005	563	8.257	613	8.495	663	8.720	713	8.934	763	9.138
414	7.453	464	7.742	514	8.010	564	8.262	614	8.499	664	8.724	714	8.938	764	9.142
415	7.459	465	7.747	515	8.016	565	8.267	615	8.504	665	8.729	715	8.942	765	9.146
416	7.465	466	7.753	516	8.021	566	8.272	616	8.509	666	8.733	716	8.946	766	9.150
417	7.471	467	7.758	517	8.026	567	8.277	617	8.513	667	8.737	717	8.950	767	9.154
418	7.477	468	7.764	518	8.031	568	8.282	618	8.518	668	8.742	718	8.955	768	9.158
419	7.483	469	7.769	519	8.036	569	8.286	619	8.522	669	8.746	719	8.959	769	9.162
420	7.489	470	7.775	520	8.041	570	8.291	620	8.527	670	8.750	720	8.963	770	9.166
421	7.495	471	7.780	521	8.047	571	8.296	621	8.532	671	8.755	721	8.967	771	9.170
422	7.501	472	7.786	522	8.052	572	8.301	622	8.536	672	8.759	722	8.971	772	9.174
423	7.507	473	7.791	523	8.057	573	8.306	623	8.541	673	8.763	723	8.975	773	9.178
424	7.513	474	7.797	524	8.062	574	8.311	624	8.545	674	8.768	724	8.979	774	9.182
425	7.518	475	7.802	525	8.067	575	8.316	625	8.550	675	8.772	725	8.984	775	9.185
426	7.524	476	7.808	526	8.072	576	8.320	626	8.554	676	8.776	726	8.988	776	9.189
427	7.530	477	7.813	527	8.077	577	8.325	627	8.559	677	8.781	727	8.992	777	9.193
428	7.536	478	7.819	528	8.082	578	8.330	628	8.564	678	8.785	728	8.996	778	9.197
429	7.542	479	7.824	529	8.088	579	8.335	629	8.568	679	8.789	729	9	779	9.201
430	7.548	480	7.830	530	8.093	580	8.340	630	8.573	680	8.794	730	9.004	780	9.205
431	7.554	481	7.835	531	8.098	581	8.344	631	8.577	681	8.798	731	9.008	781	9.209
432	7.560	482	7.841	532	8.103	582	8.349	632	8.582	682	8.802	732	9.012	782	9.213
433	7.565	483	7.846	533	8.108	583	8.354	633	8.586	683	8.807	733	9.016	783	9.217
434	7.571	484	7.851	534	8.113	584	8.359	634	8.591	684	8.811	734	9.021	784	9.221
435	7.577	485	7.857	535	8.118	585	8.363	635	8.595	685	8.815	735	9.025	785	9.225
436	7.583	486	7.862	536	8.123	586	8.368	636	8.600	686	8.819	736	9.029	786	9.229
437	7.589	487	7.868	537	8.128	587	8.373	637	8.604	687	8.824	737	9.033	787	9.233
438	7.594	488	7.873	538	8.133	588	8.378	638	8.609	688	8.828	738	9.037	788	9.237
439	7.600	489	7.878	539	8.138	589	8.382	639	8.613	689	8.832	739	9.041	789	9.240
440	7.606	490	7.884	540	8.143	590	8.387	640	8.618	690	8.837	740	9.045	790	9.244
441	7.612	491	7.889	541	8.148	591	8.392	641	8.622	691	8.841	741	9.049	791	9.248
442	7.617	492	7.894	542	8.153	592	8.397	642	8.627	692	8.845	742	9.053	792	9.252
443	7.623	493	7.900	543	8.158	593	8.401	643	8.631	693	8.849	743	9.057	793	9.256
444	7.629	494	7.905	544	8.163	594	8.406	644	8.636	694	8.854	744	9.061	794	9.260
445	7.635	495	7.910	545	8.168	595	8.411	645	8.640	695	8.858	745	9.065	795	9.264
446	7.640	496	7.916	546	8.173	596	8.416	646	8.645	696	8.862	746	9.069	796	9.268
447	7.646	497	7.921	547	8.178	597	8.420	647	8.649	697	8.866	747	9.073	797	9.272
448	7.652	498	7.926	548	8.183	598	8.425	648	8.653	698	8.871	748	9.078	798	9.275
449	7.657	499	7.932	549	8.188	599	8.430	649	8.658	699	8.875	749	9.082	799	9.279
450	7.663	500	7.937	550	8.193	600	8.434	650	8.662	700	8.879	750	9.086	800	9.283

#	Cube Root	#	Cube Root	#	Cube Root	#	Cube Root								
801	9.287	851	9.476	901	9.658	951	9.834								
802	9.291	852	9.480	902	9.662	952	9.837								
803	9.295	853	9.484	903	9.666	953	9.841								
804	9.299	854	9.488	904	9.669	954	9.844								
805	9.302	855	9.491	905	9.673	955	9.848								
806	9.306	856	9.495	906	9.676	956	9.851								
807	9.310	857	9.499	907	9.680	957	9.855								
808	9.314	858	9.502	908	9.683	958	9.858								
809	9.318	859	9.506	909	9.687	959	9.861								
810	9.322	860	9.510	910	9.691	960	9.865								
811	9.326	861	9.513	911	9.694	961	9.868								
812	9.329	862	9.517	912	9.698	962	9.872								
813	9.333	863	9.521	913	9.701	963	9.875								
814	9.337	864	9.524	914	9.705	964	9.879								
815	9.341	865	9.528	915	9.708	965	9.882								
816	9.345	866	9.532	916	9.712	966	9.885								
817	9.348	867	9.535	917	9.715	967	9.889								
818	9.352	868	9.539	918	9.719	968	9.892								
819	9.356	869	9.543	919	9.722	969	9.896								
820	9.360	870	9.546	920	9.726	970	9.899								
821	9.364	871	9.550	921	9.729	971	9.902								
822	9.368	872	9.554	922	9.733	972	9.906								
823	9.371	873	9.557	923	9.736	973	9.909								
824	9.375	874	9.561	924	9.740	974	9.913								
825	9.379	875	9.565	925	9.743	975	9.916								
826	9.383	876	9.568	926	9.747	976	9.919								
827	9.386	877	9.572	927	9.750	977	9.923								
828	9.390	878	9.576	928	9.754	978	9.926								
829	9.394	879	9.579	929	9.758	979	9.930								
830	9.398	880	9.583	930	9.761	980	9.933								
831	9.402	881	9.586	931	9.764	981	9.936								
832	9.405	882	9.590	932	9.768	982	9.940								
833	9.409	883	9.594	933	9.771	983	9.943								
834	9.413	884	9.597	934	9.775	984	9.946								
835	9.417	885	9.601	935	9.778	985	9.950								
836	9.420	886	9.605	936	9.782	986	9.953								
837	9.424	887	9.608	937	9.785	987	9.956								
838	9.428	888	9.612	938	9.789	988	9.960								
839	9.432	889	9.615	939	9.792	989	9.963								
840	9.435	890	9.619	940	9.796	990	9.967								
841	9.439	891	9.623	941	9.799	991	9.970								
842	9.443	892	9.626	942	9.803	992	9.973								
843	9.447	893	9.630	943	9.806	993	9.977								
844	9.450	894	9.633	944	9.810	994	9.980								
845	9.454	895	9.637	945	9.813	995	9.983								
846	9.458	896	9.641	946	9.817	996	9.987								
847	9.462	897	9.644	947	9.820	997	9.990								
848	9.465	898	9.648	948	9.824	998	9.993								
849	9.469	899	9.651	949	9.827	999	9.997								
850	9.473	900	9.655	950	9.830	1000	10								

Linear axes


Kepler's 3rd Law
300.00
250.00
200.00
150.00
100.00
50.00
0.00
Years
0.000
5.000
10.000
15.000
20.000
25.000
30.000
35.000
40.000
45.000
Semi-Major Axis (AU)
Why a logarithmic scale is needed:
Mercury, Venus, Earth, and Mars
are all squished together.
Jupiter
Saturn
Uranus
Neptune
Pluto