THE MASS OF JUPITER

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ABSTRACT

This report has two goals to achieve on the basis of observational data on Jupiter and its four Galilean moons (Callisto, Io, Ganymede, and Europa). By utilizing the data, we may first discover the orbital behaviors of each moon around its host planet, and then move onto calculating the mass of Jupiter by applying Kepler's laws. These moons were

1. INTRODUCTION AND PURPOSE

Galileo Galilei, an incredible and well-known astronomer of the 17th century devised an observational instrument, the telescope, that has been improved upon in great strides over time. Though Galileo's telescope can't hold a finger to say, the James Webb Space Telescope [JWST], he was still able to discern four moons surrounding the great planet Jupiter which was an incredible feat. Now, we observe these moons as they orbit Jupiter and use the pattern of orbital behavior along side Kepler's laws in order to determine the mass of Jupiter.

2. PROCEDURE

To begin, the data found in Table 1 was collected by going through nearly 30 files of astronomical data provided by Dr. Sowell. Using AstroImageJ, information about the file and the relative pixel locations from the image were obtained and recorded into Table 1. Mostly, we need to collect the coordinates of Jupiter and the four Galilean moons in each image, as well as a consideration of if the moon was above or below Jupiter relatively in order to calculate the distance of the moons to Jupiter. From AstroImageJ, we record the X_{IJ} and Y_{IJ} coordinates for each celestial body then apply a distance formula:

$$Distance = \sqrt{(X_{Jupiter} - X_{Moon})^2 + (Y_{Jupiter} - Y_{Moon})^2} \tag{1}$$

If the moon seemed to be below Jupiter, its y-value was given a negative sign. For moons that had a negative y-value, the distance was then multiplied by -1 to reflect the intuitive coordinate system.

Next, as astronomers do, we switch our focus to time. We ultimately want to graphically represent the orbital behavior of the moons around Jupiter, so we must compute a 'Running Day Number' using the Universal Time given by the FITS files. For reference, the 'Zero Day' in this case is considered September 18th, 2022. The running day is then a formula based on how many days past the Zero Day it's been and the conversion of the UT time into days, which involves breaking each component of UT time (hour/min/sec/millisec), converting each component to days, and taking the sum total. Effectively, I found that the data taken from 09/19/2022 to 10/24/2022 had a running day number ranging from 1.55 to 37.5. This running day number is represented on the x-axis of all graphs regarding the orbital behavior of the four moons.

Before we can create the graphs of the orbital behaviors, we must estimate and decide to categorize the moons in each image using its data. The easiest guesses are those with the most extreme data points, so we first try and isolate what is likely to be Callisto as it typically has the highest magnitude distance from Jupiter. To make this easier, it may be useful to graph all data points in a scatter plot and notice any patterns in extrema. This process involves a lot of comparison and editing in terms of moon guesses, though ultimately leads to neat data sets and graphs.

with these graphs, a pattern emerges and we can ascertain the amount of time one period is for each moon and use this to calculate the mass of Jupiter by applying Kepler's 3rd law.

Given as $(M_1 + M_2)P^2 = a^3$ via Newton, we ensure correct units and re-write the equation to find the orbital period equation:

$$P = \sqrt{\frac{4\pi^2 a^3}{GM}} = 2\pi\sqrt{\frac{a^3}{GM}} \tag{2}$$

where P denotes the orbital period, r defines the distance, and M defines the mass of the larger, (relatively) stationary object.

Due to a direct relationship between orbital period and mass, we can solve for Jupiter's relative mass (which is much larger than that of its moons).

$$M = \frac{4\pi^2 r^3}{GP^2} \tag{3}$$

3. RESULTS

To arrive at results from the data, we approximate sinusoidal curves onto the data and determine its orbital period from the graph. These periodic trends and the relationship described in Equation 3 are utilized to calculate the mass of Jupiter.

3.1. *Analysis*

The detailed procedure is a tedious but rewarding process. After analyzing all data, the result of all data is detailed in Table 1, describing the time stamp of when each data point is taken and its relative information to Jupiter as well as the moon it is best ascribed.

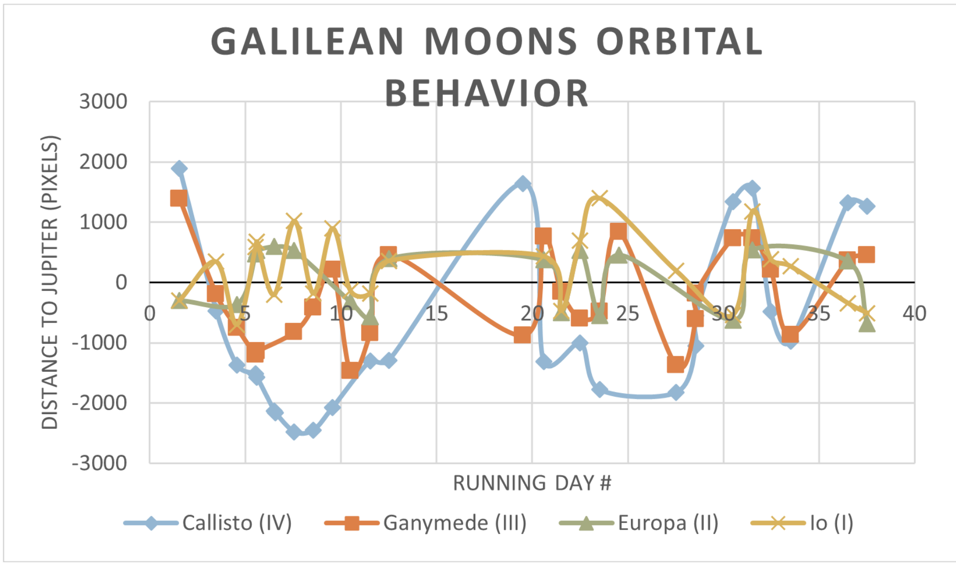

Figure 1. Orbital Period of the Four Gallilean Moons around Jupiter

After reviewing the data, a collective table of each moon's orbital period is shown in Table 1.

From this table we can see some stark differences in orbital behavior from each moon as it revolves around Jupiter. Additionally, it clearly shows some error in data collection as there is a large gap around the 15-20 Running Day which significantly alters the ability to estimate sinusoidal curves to the data, though the approximations overall seem to fit. What initially started out as a random scatter plot emerged into patterns that will lead us to great insights as we analyze each moon's orbital behavior in depth.

Overall, the data used for the Figure 1 was obtained from Table 1. With clear sinusoidal curve fits, we move on to the calculations and deep analysis for each moon.

Table 1. All Data

Date	World	X_J	Y_J	X_M	Y_M	ΔPixels
9/19/2022, T: 13:17:51.993'	Ganymede (III)	2173.171573	2424.322	1530.57	1187.257	1394.011
9/19/2022, T: 13:17:51.993'	Io (I)	2173.171573	2424.322	2290.047	2697.341	-296.983
9/19/2022, T: 13:17:51.993'	Callisto (IV)	2173.171573	2424.322	1359.111	712.3382	1895.675
9/21/2022, T: 11:21:30.489'	Io (I)	2083.101225	1436.608	2026.161	1095.051	346.2712
9/21/2022, T: 11:21:30.489'	Ganymede (III)	2083.101225	1436.608	2208.94	11578.65	-189.769
9/21/2022, T: 11:21:30.489'	Callisto (IV)	2083.101225	1436.608	2354.113	11821.08	-470.388
9/22/2022, T: 13:21:43.886'	Europa (II)	2174.047407	1245.734	2359.353	-1557.67	-362.829
9/22/2022, T: 13:21:43.886'	Io (I)	2174.047407	1245.734	2588.291	-1809.56	-699.64
9/22/2022, T: 13:21:43.886'	Ganymede (III)	2174.047407	1245.734	2498.475	-1919.5	-747.808
9/22/2022, T: 13:21:43.886'	Callisto (IV)	2174.047407	1245.734	2830.163	-2449.4	-1370.88

Table 1 *continued on next page*

Table 1 *(continued)*

Date	World	X_J	Y_J	X_M	Y_M	ΔPixels
9/23/2022, T: 12:37:44.012'	Io (I)	2139.00103	1314.581	1831.051	813.0195	588.555
9/23/2022, T: 12:37:44.012'	Europa (II)	2139.00103	1314.581	1904.85	904.3544	472.3477
9/23/2022, T: 12:37:44.012'	Ganymede (III)	2139.00103	1314.581	2667.99	-2387.71	-1196.43
9/23/2022, T: 12:37:44.012'	Callisto (IV)	2139.00103	1314.581	2913.504	-2611.14	-1510.27
09/23/2022, T: 14:29:03.774'	Io (I)	1523.622606	1101.66	1178.903	519.2026	676.8223
09/23/2022, T: 14:29:03.774'	Europa (II)	1523.622606	1101.66	1266.413	630.7089	536.6114
09/23/2022, T: 14:29:03.774'	Ganymede (III)	1523.622606	1101.66	2024.08	-2126.46	-1140.47
09/23/2022, T: 14:29:03.774'	Callisto (IV)	1523.622606	1101.66	2324.552	-2448.44	-1566.94
09/24/2022, T: 11: 55:09.653'	Europa (II)	2115.337006	1383.145	1866.936	840.2187	597.0522
09/24/2022, T: 11: 55:09.653'	Io (I)	2115.337006	1383.145	2147.224	-1585.19	-204.543
09/24/2022, T: 11: 55:09.653'	Ganymede (III)	2115.337006	1383.145	2369.863	-1858.64	-539.331
09/24/2022, T: 11: 55:09.653'	Callisto (IV)	2115.337006	1383.145	3149.877	-3240.94	-2126.43
09/24/2022, T: 13:27:53.875'	?	1588.47635	1237.859	1384.338	767.8679	512.4098
09/24/2022, T: 13:27:53.875'	Ganymede (III)	1588.47635	1237.859	1848.159	-1734.99	-560.873
09/24/2022, T: 13:27:53.875'	Callisto (IV)	1588.47635	1237.859	2634.885	-3126.09	-2158.8
09/25/2022, T:13:21:24.896'	Io (I)	1748.638691	1209.643	1228.666	328.9987	1022.696
09/25/2022, T:13:21:24.896'	Europa (II)	1748.638691	1209.643	1507.585	737.4321	530.1796
09/25/2022, T:13:21:24.896'	Ganymede (III)	1748.638691	1209.643	2145.63	-1927.67	-820.463
09/25/2022, T:13:21:24.896'	Callisto (IV)	1748.638691	1209.643	2912.457	-3395.94	-2476.77
9/26/2022, T: 13:14:57.942'	Io (I)	2206.051189	1225.202	2243.331	-1401.75	-180.436
9/26/2022, T: 13:14:57.942'	Ganymede (III)	2206.051189	1225.202	2378.463	-1595.05	-408.058
9/26/2022, T: 13:14:57.942'	Callisto (IV)	2206.051189	1225.202	3316.266	-3406.52	-2447.59
9/27/2022, T: 13:20:47.329'	Io (I)	1922.402604	1227.043	1499.822	431.15	901.1211
9/27/2022, T: 13:20:47.329'	Europa (II)	1922.402604	1227.043	1595.147	499.4423	797.8086
9/27/2022, T: 13:20:47.329'	Ganymede (III)	1922.402604	1227.043	1842.478	1026.82	215.5858
9/27/2022, T: 13:20:47.329'	Callisto (IV)	1922.402604	1227.043	2826.823	-3093.29	-2073.85
09/28/2022, T: 11:33:24.873'	Europa (II)	2144.730185	1370.766	2344.619	-1619.71	-319.262
09/28/2022, T: 11:33:24.873'	Ganymede (III)	2144.730185	1370.766	2741.025	-2707.49	-1463.69
09/28/2022, T: 11:33:24.873'	Io (I)	2144.730185	1370.766	2181.256	-1497.39	-131.789
09/29/2022, T: 12:35:00.731'	Io (I)	2191.812796	1285.83	2295.778	-1432.55	-179.823
09/29/2022, T: 12:35:00.731'	Europa (II)	2191.812796	1285.83	2360.219	-1831.69	-571.251
09/29/2022, T: 12:35:00.731'	Ganymede (III)	2191.812796	1285.83	2572.245	-2035.01	-840.242
09/29/2022, T: 12:35:00.731'	Callisto (IV)	2191.812796	1285.83	2828.185	-2418.97	-1299.6
09/30/2022, T: 12:15:52.337'	Ganymede (III)	2220.219308	1320.571	1972.013	939.3098	454.936
09/30/2022, T: 12:15:52.337'	Io (I)	2220.219308	1320.571	2033.465	1009.356	362.9493
09/30/2022, T: 12:15:52.337'	Europa (II)	2220.219308	1320.571	1948.955	1033.06	395.2809
09/30/2022, T: 12:15:52.337'	Callisto (IV)	2220.219308	1320.571	2799.94	-2468.7	-1286.19
10/06/2022, T: 12:11:48.997'	Callisto (IV)	2287.992753	1754.145	1596.133	260.9365	1645.705

Table 1 *continued on next page*

Table 1 *(continued)*

Date	World	X_J	Y_J	X_M	Y_M	ΔPixels
10/06/2022, T: 12:11:48.997’	Ganymede (III)	2287.992753	1754.145	2687.962	-2531.64	-874.34
10/06/2022, T: 12:11:48.997’	Europa (II)	2287.992753	1754.145	2878.445	-2798.34	-1199.57
10/07/2022, T: 14:15:44.938’	Ganymede (III)	2446.128253	1276.04	2187.592	559.3234	761.921
10/07/2022, T: 14:15:44.938’	Io (I)	2446.128253	1276.04	2207.345	910.4312	436.6776
10/07/2022, T: 14:15:44.938’	Europa (II)	2446.128253	1276.04	2254.856	952.7774	375.6111
10/07/2022, T: 14:15:44.938’	Callisto (IV)	2446.128253	1276.04	3037.613	-2439.69	-1305.35
10/08/2022, T: 12:22:11.164’	Ganymede (III)	2298.661149	1271.015	2443.429	-1314.09	-151.039
10/08/2022, T: 12:22:11.164’	Callisto (IV)	2298.661149	1271.015	1961.711	587.65	761.921
10/08/2022, T: 12:22:11.164’	Io (I)	2298.661149	1271.015	2596.371	-1634.91	-470.16
10/08/2022, T: 12:22:11.164’	Europa (II)	2298.661149	1271.015	2480.194	-1739.64	-502.561
10/09/2022, T: 11:59:45.889’	Io (I)	2336.18464	1294.832	1962.459	710.5593	693.5747
10/09/2022, T: 11:59:45.889’	Europa (II)	2336.18464	1294.832	2078.978	831.8981	529.5877
10/09/2022, T: 11:59:45.889’	Ganymede (III)	2336.18464	1294.832	2641.217	-1805.78	-595.077
10/09/2022, T: 11:59:45.889’	Callisto (IV)	2336.18464	1294.832	2882.497	-2133.71	-1001.09
10/10/2022, T: 12:28:15.811’	Io (I)	2328.364067	1706.814	1657.06	475.323	1402.576
10/10/2022, T: 12:28:15.811’	Ganymede (III)	2328.364067	1706.814	2517.166	-2151.97	-483.535
10/10/2022, T: 12:28:15.811’	Europa (II)	2328.364067	1706.814	2578.12	-2191.93	-545.636
10/10/2022, T: 12:28:15.811’	Callisto (IV)	2328.364067	1706.814	3215.696	-3246.73	-1777.27
10/11/2022, T: 13:03:16.940’	Callisto (IV)	2373.792564	1622.351	1909.051	667.7458	1061.723
10/11/2022, T: 13:03:16.940’	Ganymede (III)	2373.792564	1622.351	1963.359	888.7448	840.6149
10/11/2022, T: 13:03:16.940’	Europa (II)	2373.792564	1622.351	2170.669	1211.216	458.5753
10/14/2022, T: 12:27:53.320’	Io (I)	2332.431332	1171.225	2199.577	1026.552	196.4196
10/14/2022, T: 12:27:53.320’	Ganymede (III)	2332.431332	1171.225	2961.22	-2386.11	-1367.96
10/14/2022, T: 12:27:53.320’	Callisto (IV)	2332.431332	1171.225	3114.381	-2820.88	-1825.6
10/15/2022, T: 13:20:21.219’	Io (I)	2260.929208	1024.356	1905.939	313.2447	794.7939
10/15/2022, T: 13:20:21.219’	Europa (II)	2260.929208	1024.356	2450.101	-1345.29	-372.534
10/15/2022, T: 13:20:21.219’	Ganymede (III)	2260.929208	1024.356	2497.331	-1584.87	-608.326
10/15/2022, T: 13:20:21.219’	Callisto (IV)	2260.929208	1024.356	2664.228	-1996.37	-1052.36
10/15/2022, T: 13:15:53.976	Io (I)	2488.561333	1795.369	2163.43	1298.466	593.8209
10/15/2022, T: 13:15:53.977	Europa (II)	2488.561333	1795.369	2241.867	1350.099	509.042
10/15/2022, T: 13:15:53.978	Ganymede (III)	2488.561333	1795.369	2465.398	-1971.96	-178.105
10/15/2022, T: 13:15:53.979	Callisto (IV)	2488.561333	1795.369	2772.773	-2259.01	-543.82
10/17/2022, T: 11:54:31.358’	Callisto (IV)	2370.892253	1958.909	1722.539	782.3947	1343.334
10/17/2022, T: 11:54:31.358’	Ganymede (III)	2370.892253	1958.909	1943.136	1357.87	737.7149
10/17/2022, T: 11:54:31.358’	Io (I)	2370.892253	1958.909	2626.493	-2429.54	-535.564
10/17/2022, T: 11:54:31.358’	Europa (II)	2370.892253	1958.909	2633.279	-2524.08	-623.113
10/18/2022, T: 12:09:09.884’	Europa (II)	2415.044557	2324.656	2165.937	1843.508	541.8096
10/18/2022, T: 12:09:09.884’	Ganymede (III)	2415.044557	2324.656	2046.107	1686.495	737.1324

Table 1 *continued on next page*

Table 1 *(continued)*

Date	World	X_J	Y_J	X_M	Y_M	ΔPixels
10/18/2022, T: 12:09:09.884’	Io (I)	2415.044557	2324.656	1886.275	1267.398	1182.113
10/18/2022, T: 12:09:09.884’	Callisto (IV)	2415.044557	2324.656	1619.786	980.4212	1561.859
10/19/2022, T: 11:19:40.247’	Io (I)	3003.757322	1139.509	2856.535	779.6071	388.8498
10/19/2022, T: 11:19:40.247’	Ganymede (III)	3003.757322	1139.509	2957.915	931.0779	213.4134
10/19/2022, T: 11:19:40.247’	Callisto (IV)	3003.757322	1139.509	3216.209	-1567.47	-477.791
10/20/2022, T: 12:09:12.336’	Io (I)	2454.428538	1128.833	2344.917	880.8975	271.0435
10/20/2022, T: 12:09:12.336’	Ganymede (III)	2454.428538	1128.833	2862.547	-1888.21	-862.096
10/20/2022, T: 12:09:12.336’	Callisto (IV)	2454.428538	1128.833	2945.358	-1963.05	-967.951
10/23/2022, T: 11:58:01.470’	Callisto (IV)	2515.439686	2300.614	1979.497	1094.248	1320.058
10/23/2022, T: 11:58:01.470’	Ganymede (III)	2515.439686	2300.614	2297.061	2006.761	366.1134
10/23/2022, T: 11:58:01.470’	Europa (II)	2515.439686	2300.614	2333.71	1994.504	355.99
10/23/2022, T: 11:58:01.470’	Io (I)	2515.439686	2300.614	2711.302	-2579.62	-340.889
10/24/2022, T: 12:30:51.328’	Callisto (IV)	2484.485651	1615.45	1869.508	503.06	1271.066
10/24/2022, T: 12:30:51.328’	Ganymede (III)	2484.485651	1615.45	2365.768	1180.235	451.1162
10/24/2022, T: 12:30:51.328’	Io (I)	2484.485651	1615.45	2730.753	-2058.72	-507.087
10/24/2022, T: 12:30:51.328’	Europa (II)	2484.485651	1615.45	2779.251	-2230.43	-681.976

3.2. *Moon IV*

The data for Callisto (Moon IV) is listed in Table 2, showing what was used to make the phase plots relative to Jupiter. Some data points, though likely representative of Callisto, can cause the data to look more astray due to lack of surrounding data points to provide context; thereby, not all data points that are listed are represented in its respective graph.

First, before fitting the sine curve, we want to plot the points that we think belong to the moon and ensure that there are no major outliers that likely belong to another moon. This is the tedious part, but it brings out the orbial behavior pattern. The scatter plot for Callisto is shown in Figure 2.

The sinusoidal curve for Callisto is shown in Figure 3, displaying the roughly uniform curve, which is good for our calculations.

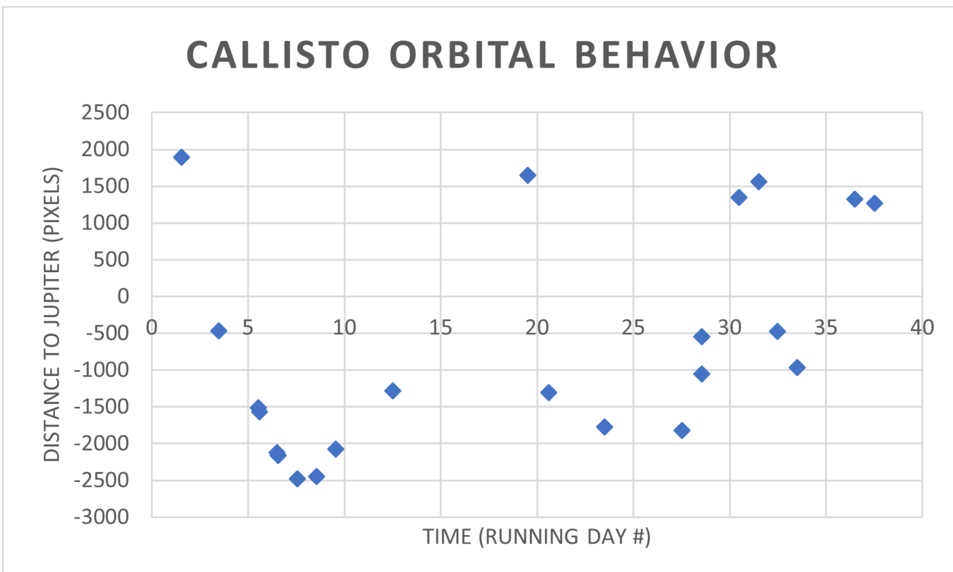

Figure 2. Scatter Points reflecting the data from Table 2

Mostly, the original data was taken day after day at around the same time, though there are occasionally gaps in the collection of data - especially as weather affects the seeing and ability to capture images of the planet and its moons. Yet, we can see from Figure 3 that the average period of orbit for Callisto is approximately 15 days, which we convert into seconds. Now, the only other variable left to define from Equation 3 is r. Here, r represented the semi-major axis from the original Equation 2, so from our data we want to choose r to be the largest distance from Jupiter, and convert this into meters using the knowledge that 92 pixels represents 1 Jupiter radius, which is about 71,500 km.

$$M = \frac{4\pi^2(1924877328)^3}{(6.674 * 10^{-11})(15 * 24 * 60 * 60)^2} = 2.51 * 10^{27} \quad kg \tag{4}$$

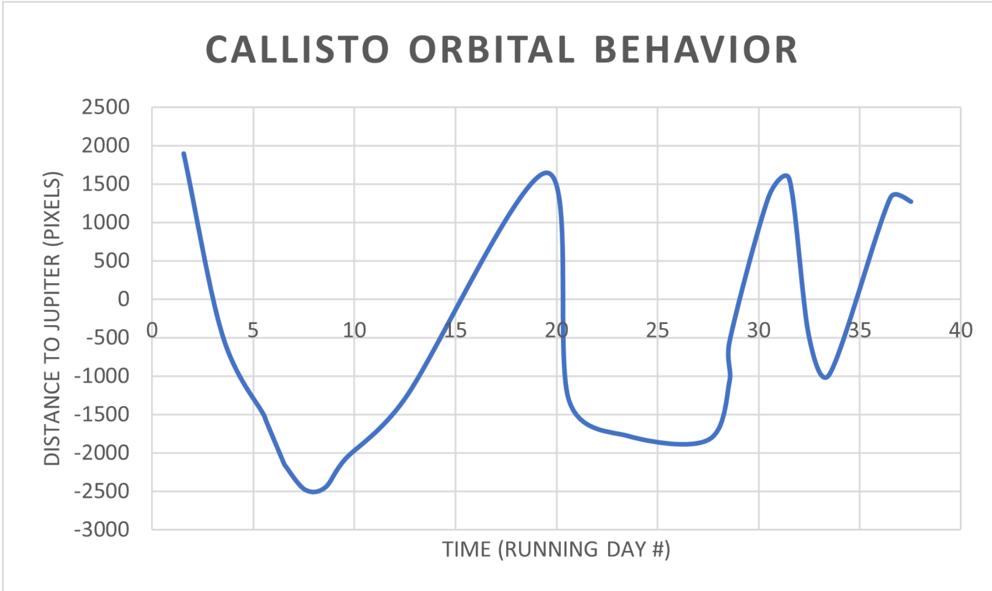

Figure 3. Sinusoidal Fit of the Callisto Data from Table 2

Using the data from Callisto, we find that the mass of Jupiter is $2.51 * 10^{27} \quad kg$, which is about a 32% error compared to the known value of Jupiter's mass.

Table 2. Moon IV Data Set

Running Day Time	ΔPixels
1.554	1895.68
3.473	- 470.39
4.556	-1370.88
5.526	-1510.27
5.604	-1566.94
6.497	-2126.43
6.560	-2158.80
7.556	-2476.77
8.551	-2447.59
9.556	-2073.85
11.52	-1299.60
12.51	-1286.19
19.51	1645.71
20.60	-1305.35
22.50	-1001.09
23.52	-1777.27
27.52	-1825.60
28.56	-1052.36
28.55	- 543.82
30.50	1343.33
31.51	1561.86
32.47	- 477.79
33.51	- 967.95
36.50	1320.06
37.52	1271.07

3.3. *Moon III*

For Ganymede (Moon III), the same process that was used for Callisto is applied. Ganymede's data is listed in Table 3 and is then graphically represented with a sine curve fit in Figure 4. We note the significantly smaller period in Ganymede's orbit compared to Callisto (about 3 days compared to 15).

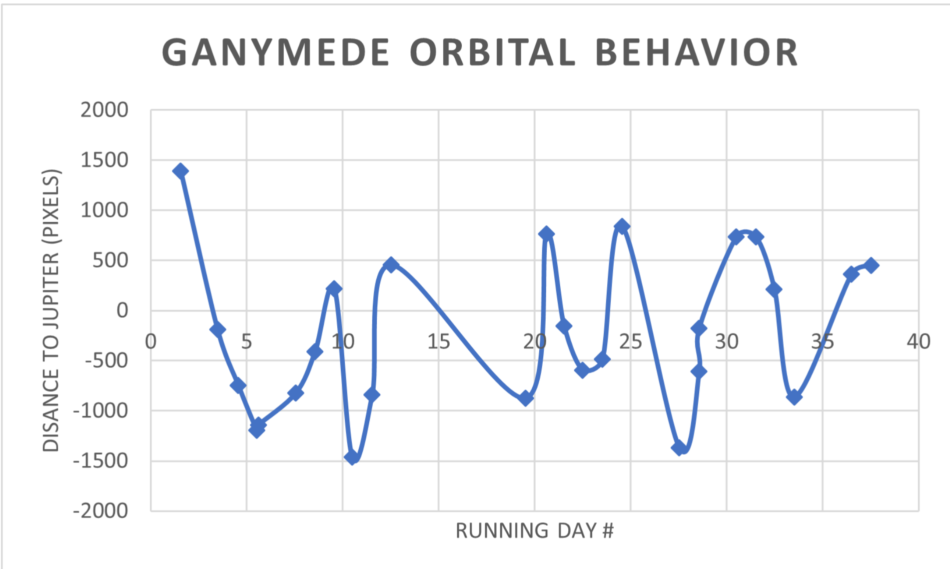

Figure 4. Sinusoidal Fit of the Ganymede Data from Table 3

Again, the same process for finding the mass is applied to the data obtained from Ganymede. We approximate the semi-major axis variable a into $r = 1137544252$ m and estimate the period to be about 3 days, which is converted into seconds for the calculation of Jupiter's mass.

Thus, Jupiter's mass given Ganymede's data is:

$$M = \frac{4\pi^2(1137544252)^3}{(6.674 * 10^{-11})(3 * 24 * 60 * 60)^2} = 1.296 * 10^{28} \quad kg \tag{5}$$

Somehow, the estimated mass of Jupiter has *significantly* increased, with a percent error over 500%. Mapping the data to Callisto was much easier than comparing to the other 3 moons. Though I experimented a lot with my guesses, there can be a lot of similarities that make it difficult to accurately assign the moon's from the images to lead to a correct graph and calculations. This value is much less accurate than that of Callisto's, unfortunately.

Table 3. Moon III Data Set

Running Day Time	ΔPixels
1.554	1394.01
3.473	- 189.769
4.556	- 747.807
5.526	-1196.43
5.604	-1140.47
7.556	- 820.463
8.551	- 408.058
9.556	215.586
10.48	-1463.69
11.52	- 840.242
12.51	454.936
19.51	- 874.340
20.59	761.921
21.52	- 151.039
22.50	- 595.077
23.52	- 83.535
24.54	840.615
27.52	-1367.96
28.56	- 608.326
28.55	- 178.105
30.50	737.715
31.51	737.132
32.47	213.413
33.51	- 862.096
36.50	366.113
37.52	451.116

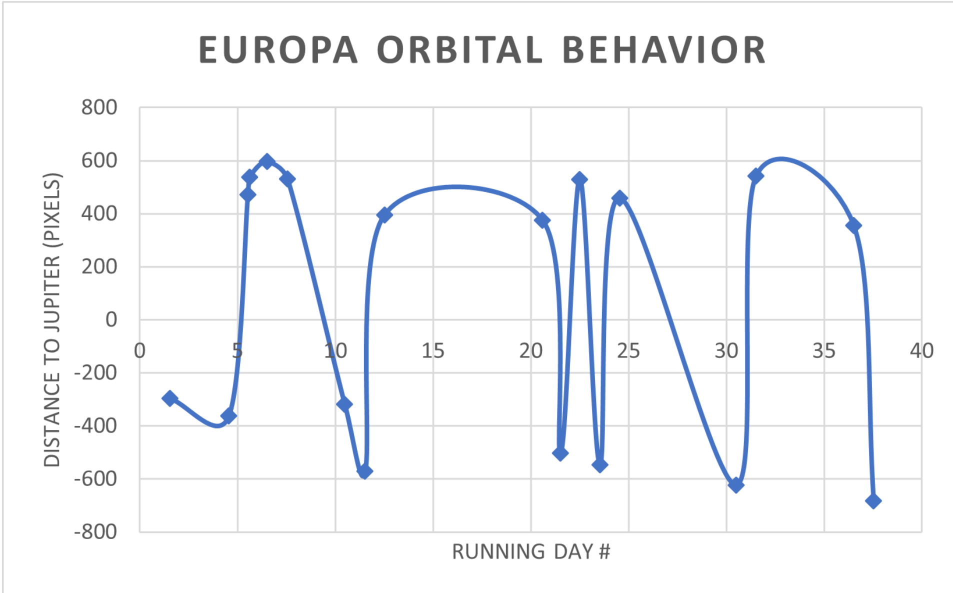

Figure 5. Sinusoidal Fit of the Europa Data from Table 4

3.4. *Moon II*

Moon II, Europa, is one of, if not the most difficult to categorize accurately. The graph for Europa is shown in Figure 5. It seems to have a small period and is generally much closer to Jupiter than the other moons have been.

From the data, Europa has an approximate period of 6 days and a maximum distance value of $r = 530013852.4$ m. Thus, we perform the calculations:

$$M = \frac{4\pi^2(530013852.4)^3}{(6.674 * 10^{-11})(6 * 24 * 60 * 60)^2} = 3.27 * 10^{26} kg \tag{6}$$

With an expected Jupiter mass of $3.27 * 10^{26}$ kg, this yields approximately an 83% error. This is actually the second best percent error, and the only value that gives a mass less than the actual mass of Jupiter.

Table 4. Moon II Data Set

Running Day Time	ΔPixels
Running Day	Distance (pixels)
1.554	-296.984
4.556	-362.829
5.526	472.348
5.604	536.611
6.497	597.052
7.556	530.180
10.48	-319.262
11.52	-571.251
12.51	395.281
20.59	375.611
21.52	-502.561
22.50	529.588
23.52	-545.636
24.54	458.575
30.50	-623.113
31.51	541.810
36.50	355.990
37.52	-681.976

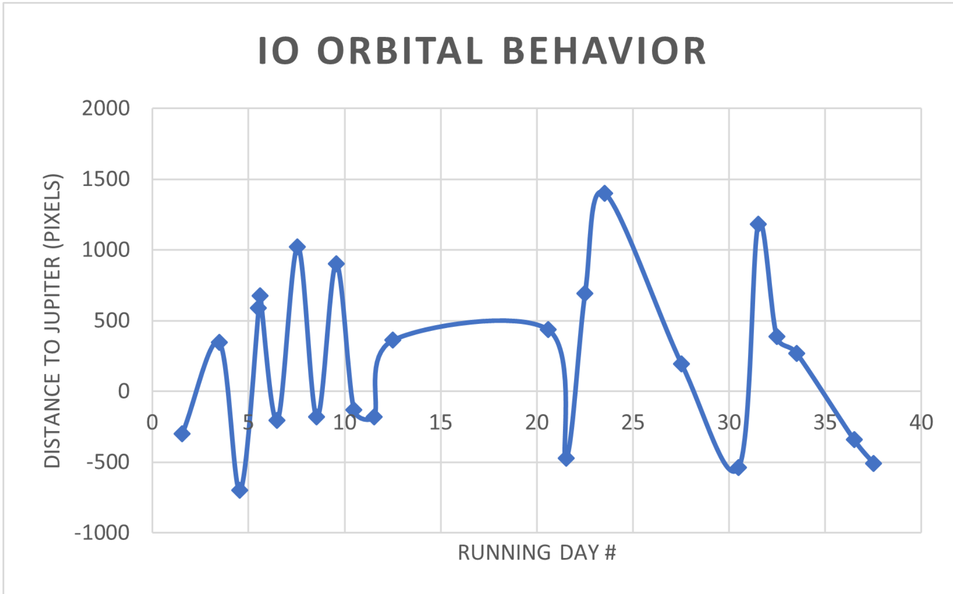

Figure 6. Sinusoidal Fit of the Io Data from Table 5

3.5. *Moon I*

Moon I, Io, was difficult to find consistent extrema points and has a very large difference in its long gap period between the 15-20 running days, but overall has a decent sinusoidal fit.

From the data, Io has an approximate period of 2 days and a maximum distance value of $r = 1,090,045,309$ m. Thus, we perform the calculations:

$$M = \frac{4\pi^2(1090045309)^3}{(6.674 * 10^{-11})(2 * 24 * 60 * 60)^2} = 8.17 * 10^{27} kg \tag{7}$$

This value of Jupiter's mass, $8.17 * 10^{27}$ yields a percent error of 330%. However, I think that this may largely be an error for some data points that are past the 15 running day number. If we restrict the graph to below that point, use the same period value, but change the r value to the highest point in the new realm, $r = 794812608.7$ m and use this equation, we arrive at a Jupiter mass value of $3.17 * 10^{27}$ kg, with a percent error of 66%, which is significantly lower. This point truly emphasizes the importance of consistent data collection and rigor in assigning the values to each moon.

Table 5. Moon I Data Set

Running Day Time	ΔPixels
Running Day	Distance (pixels)
1.554	-296.984
3.473	346.271
4.556	-699.640
5.526	588.555
5.604	676.822
6.497	-204.544
7.556	1022.69
8.551	-180.436
9.556	901.121
10.48	-131.789
11.52	-179.823
12.51	362.949
20.59	436.678
21.52	-470.160
22.50	693.575
23.52	1402.58
27.52	196.420
30.50	-535.564
31.51	1182.11
32.47	388.850
33.51	271.044
36.50	-340.889
37.52	-507.087

4. RESULTS AND CONCLUSIONS

Overall, the data obtained from Callisto was the most accurate. This is most likely due to the accurate choosing of data being the easiest to discern in terms of the data. For the most part, the order of magnitude is very close, either ± 1. The total results and comparisons with known values are shown in Table 6.

Table 6. Final Results

Moon	Mass of Jupiter (kg)	Percent Error
Callisto	$2.51 * 10^{27}$	32%
Ganymede	$1.30 * 10^{28}$	>500%
Europa	$3.27 * 10^{26}$	83%
Io	$3.17 * 10^{27}$	66%