Orbital Model of 2002 TX68 Near-Earth Asteroid

Abstract

Near-Earth asteroids can potentially be hazardous. In this project, the orbit of asteroid 2002 TX68 was observed over the span of four weeks using a 12'' LX 200 Meade telescope. Orbital elements were determined from the data gathered by finding the position and velocity vectors of 2002 TX68 using the Method of Gauss. The resulting orbital elements are: $e = 0.4314 \pm 0.0887$, $a = 2.1740 \pm 0.3490$, $i =$ is $11.1750^{\circ} \pm 1.0787$, $\Omega = 60.7462^{\circ} \pm 7.2617$, and $\omega = 146.81997^{\circ} \pm 1.514$. These orbital elements allowed for the creation of a model of the orbit of 2002 TX68 as well as the integration of the orbit forward 300,000 years using the python package REBOUND. In addition, the CHIRON spectrometer of the SMARTS telescope consortium was employed on 2002 TX68 to find the mean apparent magnitude of the asteroid at different wavelengths. The magnitude-wavelength slope was used to determine that 2002 TX68 is a blue C-type asteroid. Using this information and density information for C-type asteroids, order of magnitude calculations for the size of 2002 TX68, as well as the kinetic energy that would be released if 2002 TX68 were to hit the Earth, were conducted. It was found that 2002 TX68's closest approach to the Earth will be 0.05488 AU away. As this is much farther away from the Earth than the moon, which is located 0.00257 AU from the Earth, this study discovered that 2002 TX68 is not likely to pose a significant threat to Earth.

Orbital Model of 2002 TX68 Near-Earth Asteroid

Executive Summary

Asteroids are small rock-forming body orbiting around the sun. Although asteroids are small, they can be dangerous if they are coming to the Earth. In order to determine the threat by an asteroid, we can create an orbital model of an asteroid and learn the possibility it hitting the Earth. In this project, we used data from telescope observation and created a model for a near-earth asteroid 2002 TX68. Orbital elements were determined from the data gathered. From this model, we found that the asteroid's closest distance from the Earth will be 0.05488 AU, or 8,209,931.14 km. Since this is farther away from the Earth than the Moon, which is located 0.00257 AU, or 384,400 km, from the Earth, 2002 TX68 does not pose an immense threat to the Earth.

1 Introduction

Asteroids are small rocky, minor planets orbiting around the Sun. By studying near-earth asteroids that come within 1.5 AU of the Sun, scientists can make a model of these potentially hazardous objects' orbits, allowing us to predict the likelihood of a collision with Earth [1]. Knowing this could help us prevent such a collision by deflecting the course of the asteroid over a long period of time. It is vital to know about as many near-earth objects as possible and model their orbits because once an asteroid is on a collision course with Earth, it is hard to deflect it from that course since the asteroid can move an average of 12 miles per second [2]. Orbital models allow for long-term integration to see how close the asteroid's orbit gets to Earth and if it poses danger.

In order to predict the asteroid's closest distance from the Earth, we began by determining its orbit using observations from three different telescopes: a 16 inch reflector telescope at our research facility, a 1.3 meter Small Moderate Aperture Research Telescope System (SMARTS) I02 telescope in Cerro Tololo, Chile, and a .61-meter T24 iTelescope telescope in Auberry, California. Using the data we collected from these observations, we were able to find the asteroid's orbital elements which helped us integrate for 300,000 years to determine if it is a threat to the Earth. In addition, we were able to calculate the asteroid's size and composition using its apparent magnitude that we measured through the images that we took at the SMARTS telescope in Chile. Knowing all of this information is helpful in determining how much of a threat the asteroid poses overall to the Earth. If the asteroid is greater than 1 kilometer in diameter or is closer than 0.00257 Astronomical Unit (AU), or 384,400 km, (distance from Earth to moon) to the Earth, it could have a significant impact worldwide and is cause for concern.

2 Methods

We observed 2002 TX68 using telescopes from three locations, obtained and analyzed images to find the position of the asteroid over time, then created and improved a model for the long term orbit of the asteroid based on those locations. The 2002 TX68 was found on those telescopes using epheremises from NASA JPL Horizons. Observations were recorded on multiple nights for each telescope.

2.1 Photometry

We utilized our images to determine the apparent magnitude of our asteroid over time using MaxIm DL [MaxIm] and Stellarium [Stellarium]. To do this, we calibrated images with the asteroid by finding the magnitude of a star within each image using Stellarium and then recorded the magnitude of the asteroid in the calibrated images.

2.2 Albedo, Size, and Composition

To determine whether our asteroid is a S-type, which is composed of mainly iron or magnesium silicates, or a C-type, which is made of mostly carbonaceous chondrite, we looked at images taken from the SMARTS I02 telescope. Five images were taken in each of the four color filters B, V, R, and I. By comparing the apparent magnitudes of the asteroid in different filters, we were able to determine which type of asteroid 2002 TX68 is by using a color parameter a.

Taking the average of apparent magnitudes for each of the filters, we calculated the parameter using the following equation [need a reference here][Ivezic]:

$$a = 0.9285(v - r) + 0.3713(r - i) - 0.624$$

To further confirm the type of the asteroid, we generated a plot, with the wavelength of the color filter used on the x-axis, and the apparent magnitude of the star on the y-axis. We then interpreted the type based on the trend shown on the graph. We also calculated the color index (B-V) of 2002 TX68 by subtracting the mean magnitude of the asteroid through the V filter from the mean magnitude through the B filter, giving us an idea of its color and composition. Knowing the type of asteroid 2002 TX68 is, we found the range of albedo that is possible. The albedo is used to measure the size of our asteroid, which we can calculate using the following equation:

$$D = \frac{1329}{\sqrt{p}} 10^{-0.2H}$$

where D is the diameter of the asteroid in kilometers, p is the albedo of the asteroid, and H is the absolute magnitude of the asteroid. The absolute magnitude of an asteroid is the magnitude it would appear as if it were 1 AU from the Sun and 1 AU from the Earth, with a phase angle of zero degrees. To calculate the absolute magnitude of our asteroid, we need to know the distance from the Sun to the asteroid and the distance from the Earth to the asteroid. These two values can be acquired using JPL Horizons, and the phase angle, which is the angle between the vector from the Sun to the asteroid and the vector from the Sun to the Earth:

$$H = (V - 5\log(r\Delta)) + 2.5\log[(1 - G)\Phi_1 + G\Phi_2]$$

where H is the absolute magnitude, r is the distance of the asteroid from the Sun, Δ is the distance of the asteroid from the Earth, and G is the slope parameter, for which a value of 0.15 is assumed. The values for Φ can be calculated using the equation:

$$\Phi_i = \exp(-A_i(\tan(\frac{1}{2}\alpha)^{Bi})$$

where α is the phase angle, i is 1 or 2, A_1 = 3.33, A_2 = 1.87, B_1 = 0.63, and B_2 = 1.22. [Dymock]

2.3 Orbit Determination

We measured the centroid of the asteroid from the images of 2002 TX68 using the photo editing software DS9 and MaxIm DL. First, we found the location of the asteroid in each image. Measurements ten minutes apart were chosen. For those, we used DS9's centroid tool to find the centroid of the asteroid in each and repeated finding centroid multiple times to determine the uncertainty in our asteroid's position. It is important to find the centroid of the asteroid by finding the peak of light distribution as DS9 does because the center pixel may not necessarily be the actual centroid. Next, to find the right ascension and declination of the asteroid in each image, we used the "solve-field" functionality, a plate-solver, from Astrometry.net to map each image into the World Coordinate System and found our asteroid's position in that coordinate system. A plate-solver uses various pattern matching techniques to match the stars in the image to a given star catalog.

The next step was to find and optimize a model of the orbit of the asteroid. We will need to determine the values of orbital elements, With the right ascension, declination, and time of three data points spaced evenly through our observations, we utilized Gauss Method [3] to calculate a position and velocity vector for the center observation. First, we define the the time intervals τ_i

In our algorithm, we began with an initial ρ value of 1.5, ρ is the distance of the asteroid to the Earth. and we iterated the calculations for ten times, after which the position and velocity vectors for 2002 TX68 converged. Also we used the second order *f*-series and the third order *g* series:

$$f = 1 - \tau^2 \frac{1}{r_2^3}, g = \tau - \tau^3 \frac{1}{6r_2^3}$$

Deviations such as the travel time of light and the position of the observation site on Earth were considered when using the method. To consider the travel time of light, we iterated the Gauss Method modifying the time to account for the true position of the asteroid, sun, and Earth using the equation:

$$t_c = t_i - \frac{\rho}{c}$$

Then, the topocentric correction was made by considering the latitude and longitude we observed from using the equation:

$$R_{topo} = R_{geo} - g,$$

$$g = \mathrm{h}\cos lat \cos lst, \cos lat \sin lst, \sin lat \mathrm{i}$$

where *lst* is the local sidereal time. We obtained the local sidereal time for a given longitude and modified Julian date time using the equation:

$$lst = 24 \times (1.0027 \times jd + .277319) + \frac{longitude}{15}$$

Having obtained the position and velocity vectors at a particular time, we were able to make an orbit for the asteroid. This was done using RungeKutta 4 numerical integration to integrate the position and velocity of the asteroid forwards and backwards in time while considering the gravity of the Sun, Earth, and Jupiter on the asteroid. Thus, the expected position of the asteroid at any point in time can be found. We compared expected positions to actual measured positions of the asteroid to optimize 2002 TX68's orbit model working to minimize the sum of χ^2 for right ascension and declination:

$$\chi 2 = \Sigma(Robserved - Rexpected)2$$

where R is the right ascension or declination. We used gradient climbing to optimize our orbi, making small random changes to the components of the initial position and velocity vectors and kept the changes if they improved the model. In our method, each parameter was varied as follows: $P_{test} = P \pm X$ where X is a random, normally distributed number centered at 0 with σ = step size. For the step size, we began at .1 and divided the step size by ten every time the changes failed to improve the orbit for a thousand times in a row. We ran this algorithm until χ^2 converged.

With our final values for the position and velocity of 2002 TX68 at a given point, we were able to find the classical orbital elements of the asteroid a, **~*e***, i, Ω, and ω.

Finally, using the optimized position and velocity vectors for the asteroid, we determined the long term orbit of the asteroid using the REBOUND python package, which is able to run a numerical Nbody simulation using the WHFast integrator [Rein and Tamayo]. In our simulation, we considered the gravitational effects of the sun, Earth, and Jupiter on 2002 TX68 and integrated the orbit of the asteroid for 300,000 years (12 hours of computer runtime). In doing so, we recorded the distance of the asteroid from Earth over the time period to determine the likelihood of the asteroid impacting into Earth.

3 Results

3.1 Astrometry and Photometry

We collected data on the position and apparent magnitude of 2002 TX68 from Julian Date (JD) 2457929.60950 to JD 2457967.61368 (Table 1) using two telescopes (Table 2). We found the observation error shown in Table 1 by taking multiple centroids on the same data and measuring the difference between the measurements. Figures 1 through 9 show images of the asteroid from each of our nine observing sessions.

3.2 Orbital Model

We used the RA (α) and Dec (δ) measured at the following times to make our orbital model:

$$t_1 = 2457948.86380 \quad \alpha_1 = 20{:}15{:}07.69 \quad \delta_1 = 28{:}59{:}21.2$$

$$t_2 = 2457952.64330 \quad \alpha_2 = 20{:}18{:}44.89 \quad \delta_2 = 26{:}00{:}55.9$$

$$t_3 = 2457964.67207 \quad \alpha_3 = 20{:}29{:}02.17 \quad \delta_3 = 14{:}59{:}48.8$$

We used the rest of our data to optimize the orbit model. Our model consists of these vector elements:

$$t = 2457952.6433$$
$$r =< 0.613964, -1.09659, -0.211685 >$$
$$\dot{r} =< 0.965457, 0.401124, -0.127679 >$$

JD	Telescope	RA ± 00:00:00.1	Dec ± 00:00:01	Apparent Magnitude
2457929.60950	797	19:52:01.20	38:10:33.4	17.99
2457929.61344	797	19:52:01.49	38:10:37.2	17.99
2457929.61865	797	19:52:01.78	38:10:40.9	17.99
2457938.61812	797	20:03:38.79	35:21:01.9	17.61
2457938.62288	797	20:03:39.21	35:20:59.2	17.61
2457948.86380	U69	20:15:51.85	28:56:51.9	17.58
2457948.87170	U69	20:15:52.20	28:56:31.1	17.58
2457948.88832	U69	20:15:53.03	28:56:46.9	17.58
2457948.89786	U69	20:15:53.40	28:56:22.3	17.58
2457952.61519	797	20:19:27.62	26:00:08.6	17.15
2457952.62265	797	20:19:27.96	25:59:46.0	17.15
2457952.63148	797	20:19:28.33	25:59:19.8	17.15
2457952.63737	797	20:19:28.63	25:59:02.4	17.15
2457952.64330	797	20:19:28.83	25:58:44.9	17.15
2457955.62155	797	20:21:16.75	24:15:23.4	17.11
2457955.62999	797	20:21:16.20	24:15:08.1	17.11
2457955.63833	797	20:21:17.21	24:14:28.9	17.11
2457955.65034	797	20:21:16.41	24:13:59.2	17.11
2457955.82300	U69	20:21:26.96	24:04:33.4	16.96
2457955.79778	U69	20:21:27.63	24:03:40.2	16.96
2457964.66499	797	20:29:00.16	15:02:16.5	16.90
2457964.67207	797	20:29:00.45	15:01:46.9	16.90
2457964.67840	797	20:29:00.62	15:01:21.0	16.90
2457964.69162	797	20:29:01.15	15:00:27.9	16.90
2457964.69866	797	20:29:01.43	14:59:59.4	16.90
2457966.71145	797	20:30:41.80	12:41:40.8	16.76
2457966.71745	797	20:30:41.77	12:41:55.2	16.76
2457966.72112	797	20:30:41.57	12:42:18.7	16.76
2457967.61368	797	20:31:27.53	11:39:27.8	16.70
2457967.62059	797	20:31:27.81	11:38:58.6	16.70
2457967.63512	797	20:31:28.38	11:37:57.9	16.70
2457967.64203	797	20:31:28.65	11:37:29.8	16.70
2457967.64618	797	20:31:27.85	11:37:12.2	16.70

Table 1: Astrometry and Photometry Data

Observatory	JPL Code Number	Latitude	Longitude	Aperture
Research Institution	797	287°04’ 30.4” E	41°18’ 58.8” N	0.406 m
iTelescope T24	U69	240°35’ 13.2” E	37°04’ 13.4” N	0.610 m
Cerro Tololo, Chile	I02	289°11’ 41.6” E	30°10’ 03.8” S	1.3 m

Table 2: Telescope Information

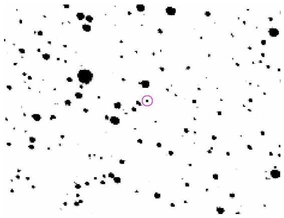


Figure 1: 2002 TX68 on JD 2457929

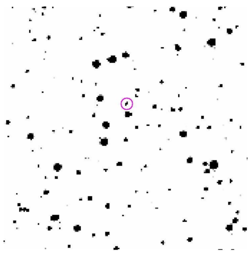


Figure 2: 2002 TX68 on JD 2457938

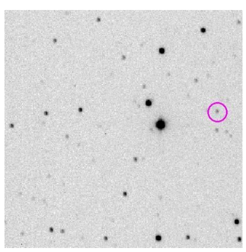


Figure 3: 2002 TX68 on JD 2457948

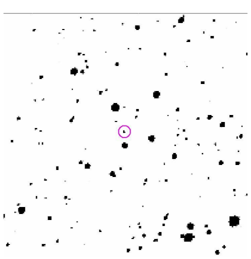


Figure 4: 2002 TX68 on JD 2457952

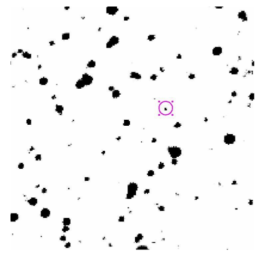


Figure 5: 2002 TX68 on JD 2457955 (Leitner)

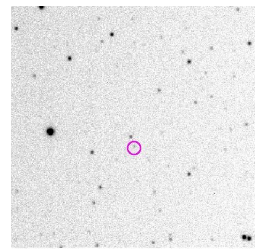


Figure 6: 2002 TX68 on JD 2457955 (U69)

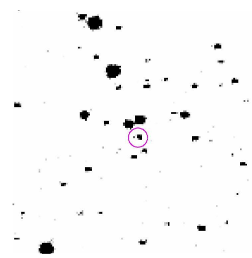


Figure 7: 2002 TX68 on JD 2457964

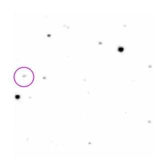


Figure 8: 2002 TX68 on JD 2457966

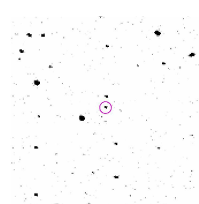


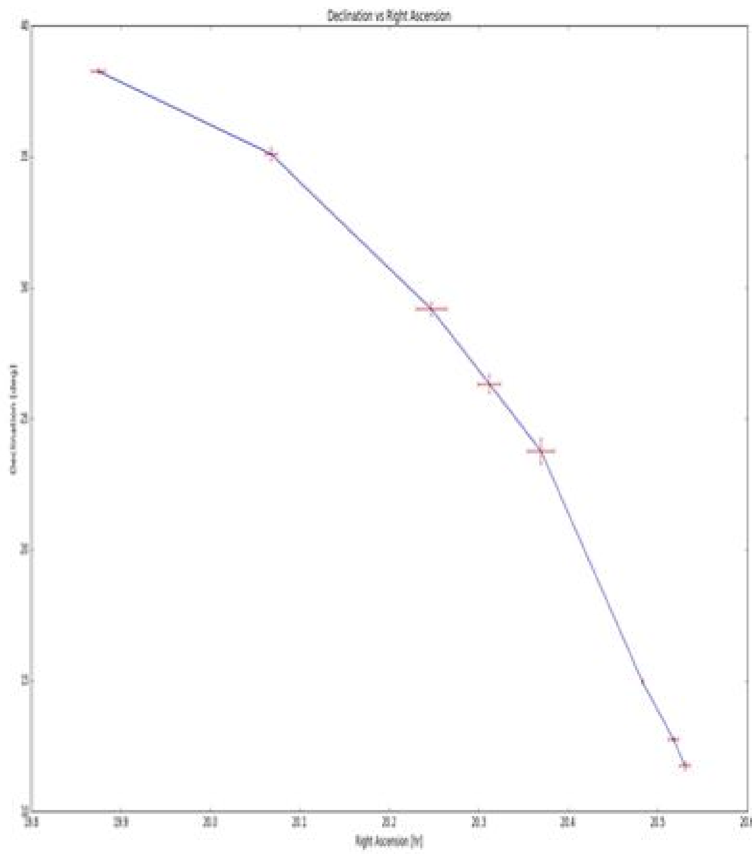
Figure 9: 2002 TX68 on JD 2457967

JD	Predicted by Orbital Model		Observed		Residuals	
	RA	Dec	RA	Dec	RA	Dec
2457929.60950	19:52:28.70	38:15:52.7	19:52:01.20	38:10:33.4	0:00:27.5002	0:05:19.348
2457929.61344	19:52:26.06	38:16:01.5	19:52:01.49	38:10:37.2	0:00:24.5731	0:05:24.276
2457929.61865	19:52:22.57	38:16:13.0	19:52:01.78	38:10:40.9	0:00:20.7939	0:05:32.091
2457938.61812	20:04:04.85	35:06:19.1	20:03:38.79	35:21:01.9	0:00:26.0644	0:14:42.840
2457938.62288	20:04:01.47	35:06:25.0	20:03:39.21	35:20:59.2	0:00:22.2641	0:14:34.174
2457948.86380	20:14:49.53	29:11:30.9	20:15:51.85	28:56:51.9	0:01:02.3185	0:14:38.971
2457948.87170	20:15:29.30	29:09:10.2	20:15:52.20	28:56:31.1	0:00:22.8986	0:12:39.141
2457948.88832	20:15:17.15	29:09:04.3	20:15:53.03	28:56:46.9	0:00:35.8778	0:12:17.403
2457948.89786	20:15:10.18	29:09:00.8	20:15:53.40	28:56:22.3	0:00:43.2183	0:12:38.515
2457952.61519	20:18:41.81	26:20:29.3	20:19:27.62	26:00:08.6	0:00:45.8060	0:20:20.679
2457952.62265	20:18:36.34	26:20:24.2	20:19:27.96	25:59:46.0	0:00:51.6157	0:20:38.233
2457952.63148	20:18:29.87	26:20:18.1	20:19:28.33	25:59:19.8	0:00:58.4637	0:20:58.350
2457952.63737	20:18:25.54	26:20:14.0	20:19:28.63	25:59:02.4	0:01:03.0869	0:21:11.625
2457952.64330	20:18:21.19	26:20:09.8	20:19:28.83	25:58:44.9	0:01:07.6405	0:21:24.917
2457955.62155	20:22:16.42	23:46:02.3	20:21:16.75	24:15:23.4	0:00:59.6670	0:29:21.134
2457955.62999	20:22:10.26	23:45:52.8	20:21:16.20	24:15:08.1	0:00:54.0587	0:29:15.280
2457955.63833	20:22:04.17	23:45:43.4	20:21:17.21	24:14:28.9	0:00:46.9602	0:28:45.523
2457955.65034	20:21:55.40	23:45:29.6	20:21:17.41	24:13:59.2	0:00:37.9874	0:28:29.612
2457955.79778	20:22:22.44	23:36:35.3	20:21:26.96	24:04:33.4	0:00:55.4768	0:27:58.069
2457955.82300	20:22:04.03	23:36:01.6	20:21:27.63	24:03:40.2	0:00:36.4004	0:27:38.610
2457964.66499	20:29:03.03	14:58:06.6	20:29:00.16	15:02:16.5	0:00:02.8746	0:04:09.948
2457964.67207	20:28:58.05	14:57:49.7	20:29:00.45	15:01:46.9	0:00:02.4005	0:03:57.228
2457964.67840	20:28:53.59	14:57:34.5	20:29:00.62	15:01:21.0	0:00:07.0277	0:03:46.475
2457964.69162	20:29:27.39	14:55:37.2	20:29:01.15	15:00:27.9	0:00:26.2387	0:04:50.716
2457964.69866	20:29:22.43	14:55:20.2	20:29:01.43	14:59:59.4	0:00:21.0027	0:04:39.187
2457966.71145	20:30:27.53	12:47:20.7	20:30:41.80	12:41:40.8	0:00:14.2699	0:05:39.938
2457966.71745	20:31:05.88	12:45:46.1	20:30:41.77	12:41:55.2	0:00:24.1122	0:03:50.944
2457966.72112	20:31:03.33	12:45:36.5	20:30:41.57	12:42:18.7	0:00:21.7649	0:03:17.765
2457967.61368	20:31:29.71	11:48:17.2	20:31:27.53	11:39:27.8	0:00:02.1769	0:08:49.427
2457967.62059	20:31:24.95	11:47:59.2	20:31:27.81	11:38:58.6	0:00:02.8611	0:09:00.556
2457967.63512	20:31:14.94	11:47:20.9	20:31:28.38	11:37:57.9	0:00:13.4396	0:09:23.047
2457967.64203	20:31:10.18	11:47:02.7	20:31:28.65	11:37:29.8	0:00:18.4703	0:09:32.880
2457967.64618	20:31:49.55	11:45:35.9	20:31:27.85	11:37:12.2	0:00:21.7017	0:08:23.749

Table 3: Comparison of Predicted and Observed RA and Dec

Orbital Element	Orbital Model Predictions	JPL Values
Eccentricity	0.431400 ± 0.088742	0.293711
Semi-Major Axis (AU)	2.17404 ± 0.34895	1.67393
Inclination (degrees)	11.1750 ± 1.0787	16.6468
Longitude of the Ascending Node (degrees)	60.7462 ± 7.2617	150.206
Argument of Perihelion (degrees)	146.820 ± 1.514	122.349

Table 4: Orbital Elements and Uncertainty



We compared the RA and Dec predicted by our model at each observation time with the actual values observed at those times in Table 3. RA, Dec, and error bars for each of our nine observation sessions is represented graphically in Figure 10.

From the residuals we calculated the χ^2 for RA and Dec:

$$\chi^2_{RA} = 0.785711$$
$$\chi^2_{Dec} = 2.45875$$

We used the orbit model to find the classical orbital elements. In order to calculate uncertainty due to measurement error, we created four new orbital models. Each model was based on the upper and lower bounds of our measured RA and Dec (see Table 1) for the same t_1, t_2, t_3 used to create our main orbital model. Just as we did for our main orbital model, we used ten iterations of Method of Gauss to create the four models for testing uncertainty. However, we did not attempt to optimize these models, as we did with the main model. We calculated classical orbital elements from each of these four models. Then we found the differences between the values of the elements predicted by

each of the four models and the values predicted by our main orbit model. We estimated uncertainty for each orbital element based on the greatest difference (Table 4).

3.3 Albedo, Size, and Composition

JD	Apparent Magnitude	Filter
2457969.71961	16.395	B
2457969.72090	16.264	B
2457969.72219	16.211	B
2457969.72348	16.300	B
2457969.72478	16.204	B
2457969.72620	16.478	V
2457969.72749	16.479	V
2457969.72878	16.502	V
2457969.73007	16.478	V
2457969.73136	16.516	V
2457969.73278	16.527	R
2457969.73408	16.688	R
2457969.73537	16.623	R
2457969.73666	16.629	R
2457969.73795	16.650	R
2457969.73941	16.769	I
2457969.74070	16.828	I
2457969.74199	16.886	I
2457969.74328	15.095	I
2457969.74458	16.858	I

Table 5: The Apparent Magnitude of the asteroid seen through different color filters.

We calculated the color parameter a to be -0.822, which is less than or equal to zero. Therefore, according to Jia Hui, *et. Al*, our asteroid is a C-type asteroid, subtype B. A C-type asteroid has an albedo range from 0.02 to 0.05.

Plotting the mean apparent magnitude of the asteroid through each of the different filters with the wavelength of the color filter used, we find a smooth negative curve, a characteristic of a C-type asteroid. The color index (B-V) of the asteroid was found to be -0.216 ± 0.071. This means that the 2002 TX68 has a very blue color, rare among asteroids.

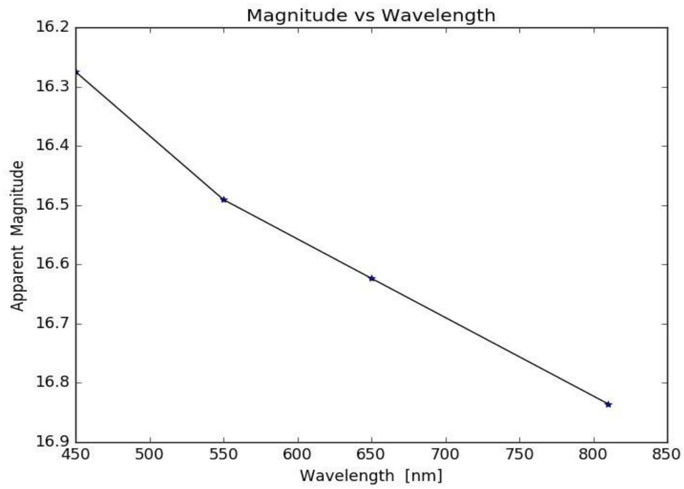


Figure 11: The Magnitude vs. Wavelength graph shows that the 2002 TX68 is a C-type asteroid

After acquiring the Earth to Sun, Earth to Asteroid, and Sun to Asteroid vectors from JPL Horizons, we used the equations to calculate that the absolute magnitude of 2002 TX68 is 22.775±0.2. Using this value, along with an albedo ranging from 0.02 to 0.05, we calculated that the diameter of the asteroid is 0.213 ± 0.05 kilometers.

3.4 Long Term Orbit and Threat Simulation

It is very unlikely that 2002 TX68 will hit the Earth in the next three hundred thousand years. Our REBOUND simulation found that the closest passage of 2002 TX68 to the Earth in the next 300,000 years is .05 AU, or 4,648,000 miles away from Earth. This is over ten times the distance from the Earth to the moon. This periapsis will occur around Julian day 3464139, in May 4772. The orbit of 2002 TX68 over the long term is periodic relative to Earth and the asteroid reaches periapsis around every 1200 days. The particular periapsis distance varies based on the position of the Earth as well as Jupiter, which perturb the asteroid from its regular orbit.

Because the closest passage to Earth for 2002 TX68 occurs in around 1500 years for a 300,000 year time period, TX68 is getting further and further away from the Earth in that period. Therefore, it is unlikely that TX68 will ever hit Earth.

Even though it is unlikely that 2002 TX68 will hit the Earth, we can calculate the kinetic energy that would be transferred by 2002 TX68 if its orbit were to change and it did. The kinetic energy of an object is:

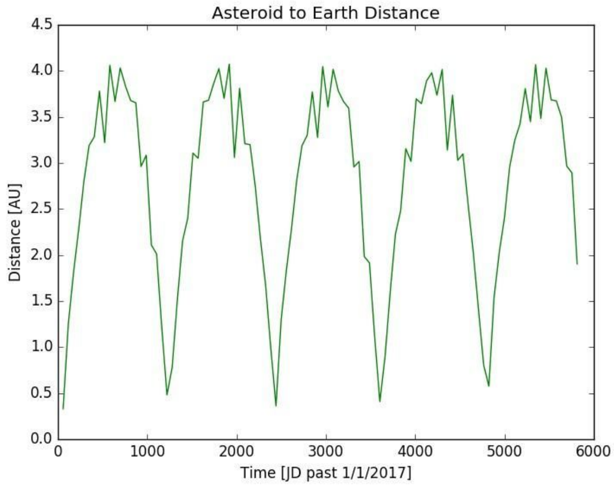
$$KE = \frac{1}{2} \times mv^2$$

Using REBOUND, we found that the velocity of the asteroid at Julian day 3464139 is .31 AU per Figure 12: The asteroid to Earth distance is fairly periodic

modified day, or $8 * 10^9$ meters per second. We can calculate the mass of our asteroid based on its diameter if we model it as a sphere. The density of a C type asteroid is, on average, 1380 $\frac{kg}{m^3}$. [Krasinsky, 2007] Then, the mass of an asteroid with diameter d should be

$$m = \frac{4\pi}{3} \times (\frac{d}{2})^3$$

We found the mass of 2002 TX68 to be $6 * 10^9$ kilograms, and the kinetic energy of collision on the order of 10^{27} joules. This is an incredible amount of energy equal to billions of times of the energy of even the strongest nuclear bombs in existence. However, due to the small size of 2002 TX68 it is likely that much of the asteroid would burn up in the atmosphere before actually reaching the ground, mitigating the impact significantly.



4 Conclusion

4.1 Orbital Model

Our orbital model is incompatible with JPL Horizons. The JPL classical orbital elements for 2002 TX68 are outside the error bars of the classical orbital elements calculated according to our model (Table 4). Our values for eccentricity and longitude of the ascending node are especially far from the JPL values. These discrepancies are likely not due to observation error, as our observations for RA and Dec were very close to the JPL values. Rather, these discrepancies are due to the facts that we observed the asteroid for a relatively short period of time while it was moving almost parallel to Earth. We believe that the discrepancy is due to an error in our model, not in JPL, as JPL's model is based on a longer period of observations. Of course, it is also possible that we are correct and JPL is wrong.

4.2 Long Term Threat Simulation

For long term orbit and threat simulation, our simulation showed that the closest passage of 2002 TX68 to the Earth will be much farther away from the Earth than the moon is, meaning that the probability that the asteroid will hit Earth is extremely small. When the simulation results were graphed, it showed that the asteroid to Earth distance over the range of 300,000 years increases as time goes on. 2002 TX68 is moving further away from the Earth as time goes on meaning that impact is even less likely. Although impact is unlikely, this asteroid has immense kinetic energy. But, even if the asteroid did come through Earth's atmosphere, most of it will burn up before it actually reaches the ground, due to its small size. While it is in the atmosphere, we would be able to see its rare blue color and further study its composition before it disappears. In short, based on our observations and calculations, the asteroid 2002 TX68 does not pose any immediate threat to the Earth.

References

[1] InternationalAstronomicalUnion.Symposium. *Near Earth Objects, Our Celestial Neighbors (IAU S236): Opportunity and Risk*. Cambridge University Press, 2007. ISBN 9780521863452. URL https://books.google.com/books?id=QQx8r1$_T$*PQEC.*

[2] Bill Keeter. *Planetary Defense- Frequently Asked Questions*. NASA. URL https://www.nasa.gov/planetarydefense/faq.

[3] Howard D. Curtis. *Orbital Mechanics for Engineering Students*. Butterworth-Heinemann, 2014.

[MaxIm] MaxIm DL software. URL http://diffractionlimited.com/product/maxim-dl/

[Stellarium] Stellarium. URL http://www.stellarium.org

[IVezic] Željko Ivezić, et al. "Color confirmation of asteroid families." The Astronomical Journal 124.5 (2002): 2943.

[4] Renno Rein and Daniel Tamayo. *WHFast: A fast and unbiased implementation of a symplectic Wisdom-Holman integrator for long term gravitational simulations*. Cornell University Library.
URL https://arxiv.org/abs/1506.01084.

[Dymock] Roger Dymock. *The H and G Magnitude System for Asteroids*. The BAA Observers' Workshops.

[Krasinsky, 2007] Pitjeva E. V. Vasilyev M. V. Yagudina E. I. Krasinsky, G. A. *Hidden Mass in the Asteroid Belt*. Icarus, 2007. ISBN 9780521863452. URL https://books.google.com/books?id=QQx8r1$_T$*PQEC.*