Using Telescopic Observation to Determine the Orbital Elements of Asteroid 1998 RO4

Team 6

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Abstract

Near-Earth asteroids have the potential to collide with Earth, which may cause millions of deaths. Our goal is to determine the six orbital elements and absolute H-magnitude of near-Earth asteroid 1998 RO4 to determine its long-term dynamical behavior in order to evaluate the risk that it poses to Earth. An ephemeris (semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of periapsis, mean anomaly) was generated using ground-based observations and Gauss's method. Orbital element uncertainties were calculated using a Monte Carlo simulation. Numerical integration was used to simulate 60 possible 1998 RO4 trajectories. Out of the 60 simulated bodies, over the course of 50 million years, 25.00% remained in orbit, 13.33% crashed into the sun, and 61.67% were ejected from the solar system. None of the simulated bodies crashed into the Earth; it is improbable that 1998 RO4 poses a risk to Earth within the next 50 million years.

1. Introduction

Asteroids are irregularly shaped rocky bodies with elliptical orbits around the Sun. Made out of leftover material from the formation of the Solar System, asteroids are a form of solar debris similar to comets and meteors. Most asteroids are located between Mars and Jupiter in the Main Asteroid Belt, around 2.2 - 3.2 AU from the Sun. Asteroids are placed into three categories based on their material composition: C-type (carbonaceous), S-type (silicate), and M-type (metal) (University of Arizona).

Asteroids with a perihelion distance of less than 1.3 AU are called near-Earth asteroids. Most near-Earth asteroids originate from the Main Asteroid Belt; Jupiter's gravitational influence or collisions with other asteroids shift these asteroids' orbits inwards. Near-Earth asteroids are classified into four groups. Atira Asteroids have orbits wholly contained inside the orbit of the Earth. Aten Asteroids are Earth-crossing asteroids with semi-major axes less than 1 AU. Apollo asteroids are also Earth-crossing but have semi-major axes larger than 1 AU. Finally, Amor Asteroids lie between Earth and Mars and may cross the orbit of Mars ("Near Earth Asteroids | COSMOS"). This study determines the orbit of the Amor Asteroid 1998 RO4. It has a perihelion distance of 1.23 AU and only intersects the orbit of Mars.

It is vital to keep track of near-Earth objects (NEO) because of their potential to collide with Earth and endanger millions of lives. By tracking their positions, it is possible to anticipate collisions and develop prevention plans (Binzel). Search campaigns like the Near-Earth Object Observations Program fund efforts to search for undiscovered NEOs, refine NEO orbit calculations, and develop deflection and mitigation technologies ("NEO Observations Program").

The orbit of an asteroid is described by its six orbital elements: semi-major axis (a), eccentricity (e), inclination (i), longitude of the ascending node (Ω), argument of perihelion (ω), and mean anomaly (M) (See Figure 1). The semi-major axis is the length of the longest semi-diameter of the elliptical orbit. Eccentricity describes how much the orbit deviates from a circle. Inclination is the angle between the asteroid's orbital plane and the ecliptic plane. The longitude of the ascending node specifies the angle between the vernal equinox and the ascending node. The argument of perihelion measures the angle between the ascending node and the point at which the orbit is at perihelion (closest to the Sun). The mean anomaly is an angle, starting at periapsis, proportional to the fraction of the period the asteroid has gone through. The purpose of this value is to simplify calculations for future positions.[1] Figure 1 visually displays these elements and their positions in space (Binzel).

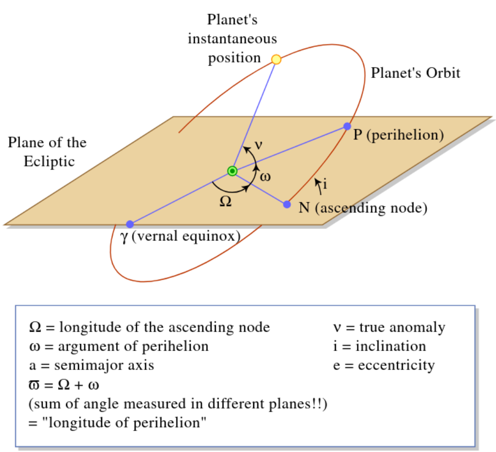

Figure 1. *The 6 orbital elements of an asteroid: semi-major axis, eccentricity, inclination, longitude of the ascending node, argument of perihelion, and true anomaly[1] (Binzel)*

The method of Gauss was used to calculate the orbit of 1998 RO4. The method uses three data points (i.e., observations) that each contain the right ascension and declination at a given observation time. Gauss's method repeatedly recalculates the position and velocity vector of the asteroid until they converge.

2. Observations and Image Processing

2.1. Data Acquisition

Two 20" telescopes at the Sommers-Bausch Observatory (observatory code: 463) were used to take images of 1998 RO4. These telescopes have f/6.8 focal lengths, a UV/IR Cut filter installed, a field of view of 16.5'x12.4', and a SBIG STF-8300M CCD ("20-inch PlaneWave Telescopes | Sommers-Bausch Observatory"). Asteroid sky coordinates were found using the JPL Horizons ephemeris service. Five dome flats, five flat darks, and five standard darks were taken during each observation session. For each observation, three sets of three lights were taken at ten-minute intervals. Details for the five observations are recorded in Table 1.

Date & Start Time	Obs #	Telescope
2023-06-21 6:26:22.335	1	West
2023-06-25 06:33:58.129	2	West
2023-06-27 6:26:2.155	3	West
2023-07-10 06:21:54.022	4	East
2023-07-14 06:30:20.651	5	East

Table 1. *All observations were taken at Sommers-Bausch Observatory at University of Colorado Boulder. The observatory has two identical telescopes: West ("Apollo") and East ("Artemis"); Apollo was used for the first three observations and Artemis was used for the last two observations. Observations 2, 3, and 4 were used when calculating orbital elements. All images had an exposure time of 60 seconds.*

[1] Mean anomaly is used in place of true anomaly when future predictions need to be made.

2.2. Image Reduction

Standard flat and dark correction procedures were used. AstroImageJ (AIJ) was used for all image processing. AIJ and nova.astrometry.net were used to plate solve images to determine the right ascension (RA/α) and declination (Dec/δ) of 1998 RO4. SAOImageDS9 was used to determine the relative R magnitude of 5-6 reference stars utilizing the UCAC 4 catalog. The source-sky counts (fluxes) for each of the reference stars and the asteroid were retrieved from AIJ.

2.3. Determination of Errors in Astrometry

To analyze the right ascension and declination of each observation, each image was plate solved through nova.astrometry.net. Each successful plate solution provided a corr.fits file which contains a table of measured and expected locations for every object used in the fitting process. To determine the errors in astrometry, the standard deviations of the right ascensions and declinations were calculated by solving the root mean square of the difference between the measured (x_f) and expected (x_i) locations, along with the total number of stars used (N) (See Equation 1).

$$\sqrt{\frac{\sum(x_f - x_i)^2}{N}} \quad (1)$$

2.4. Results

Plate solving observations 2, 3, and 4 resulted in the RA and Dec values presented in Table 2. These results were then used for orbit determination using the method of Gauss. The error bars given in this table were obtained from the root mean square of the star positions in the image vs. those given by the plate solve.

Time (UTC)	Julian Date (JD-2460100)	RA (°)	dec (°)
2023-06-25 06:33:58.129	20.773589	20h 25m 17.31s ±0.02s	4º 1’ 30.7” ±0.2”
2023-06-27 06:26:2.155	22.768081	20h 29m 38.70s ±0.01s	4º 43’ 30.3” ±0.1”
2023-07-10 06:21:54.022	35.765208	20h 57m 20.26s ±0.01s	8º 35’ 50.5” ±0.1”

Table 2. *The measured RA and Dec values for asteroid 1998 RO4.*

3. Orbit Determination

3.1. Methods

The position and velocity vectors cannot be analytically determined. Gauss’s method was programmed in Python to numerically estimate the position and velocity vectors for the middle observation time (t_2) from the RA and Dec of the asteroid on three observations (i.e., given three instances of α_i, δ_i, t_i) and from the Sun vector at those times. The method of Gauss requires three data points to fit an orbit. Two extra observations were recorded in case the three initially tested observations did not converge. Observations 2, 3, and 4 were tested and successfully converged, so observations 1 and 5 were not used. The method of Gauss recursively computes the position and velocity vectors until it converges within 10^{-10} of the last calculated value.

Orbital elements were calculated in Python using the position and velocity vectors from Gauss’s method.

A 10,000-iteration Monte Carlo simulation was programmed using Python to generate a normal distribution of each orbital element. The Monte Carlo simulation used the standard deviation (See *Section 2.3*) to generate a Gaussian distribution for the RA and Dec of the asteroid on the middle observation (Obs 3). This distribution of RA and Dec values was used to generate normal distributions for each orbital element, as shown in Figure 3.

Ephemeris generation code was programmed in Python to verify the accuracy of the orbital elements. The ephemeris generation program used the orbital elements to determine the

RA and Dec of the asteroid at a different time. Using the orbital elements calculated for observation 3 (t_2), an ephemeris was generated for observation 4 (t_3). The ephemeris-generated RA was off 36.4 seconds from the observed RA; the ephemeris-generated Dec was off 18 arc seconds from the observed Dec.

To determine the relative R magnitude of the asteroid, a log base 10 source-sky counts[2] vs. relative R magnitude plot was created using 5-6 reference stars. Reliable plots[3] were successfully generated for ten distinct images across the five observations. Using the line of best fit generated by the data, the log base 10 of the asteroid can then be converted into the asteroid's R magnitude.

The absolute H magnitude of an asteroid (H-mag) is defined as the observed magnitude of an asteroid if it were placed 1 AU away from the observer (NASA). It is impossible to observe this from the Earth directly; however, it can be calculated using the distance from the Earth to the Sun, the distance from the Earth to the asteroid, the angle between those vectors, and the apparent magnitude at that moment (See Figure 2). This calculation relies on an estimation of G (the gravitational constant); however, a value of 0.15 will result in a relatively accurate value.

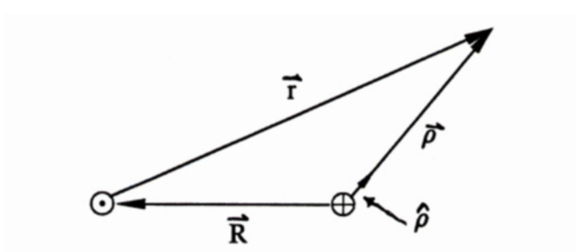

Figure 2. *This diagram shows the relationship between the R vector,* **ρ** *vector, angle between R and* **ρ***, and its use in calculating the Hmag.*

3.2. Results

The orbital elements were calculated from the RA and dec of 1998 RO4 during observations 2, 3, and 4 (See Table 3 for orbital elements). The standard deviations[4] (σ) of the orbital elements were determined using a 10,000-iteration Monte Carlo simulation (See Figure 3, Table 3). The histograms in Figure 3 display the variations in the six orbital elements based on previously calculated normal distributions of RA and Dec.

Figure 4 uses the calculated semi-major axis and eccentricity to visualize the size and shape of 1998 RO4's orbit. In addition, Figure 4 shows that the periapsis of 1998 RO4 never comes within 1 AU of the Sun, meaning that even though it is a near-Earth asteroid, it will not come into contact with the Earth.

An H-mag of 18.6 was determined using vectors generated by JPL Horizons and R mags found in observations.

Orbital Element	Predicted Value	σ
a	2.130 AU	0.009 AU
e	0.423	0.002
i	5.36°	0.01°
Ω	191.77°	0.08°
ω	111.95°	0.10°
M	352.09°	0.06°

Table 3. *All 6 orbital elements matched with uncertainties (Standard Deviation), mean anomaly is for 2023 June 27 6:26:2.155*

[2] The relative magnitude scale is logarithmic.
[3] When a source-sky count vs. relative R magnitude plot is linearized to log base 10, it should form a slope of -2.5. A reliable plot has a line of best fit slope within 0.3 of -2.5.

[4] Calculated using the root mean square; see Section 2.3

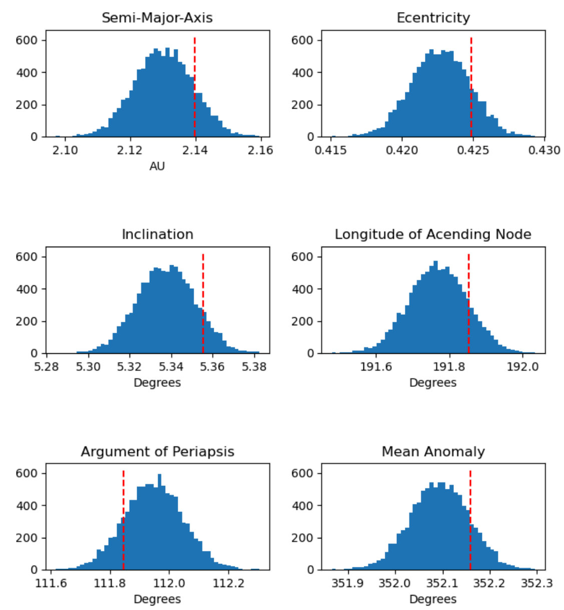

Figure 3. *Six histograms show the output orbital elements from a Monte Carlo simulation using 10,000 runs; the red lines represent the values from JPL Horizons.*

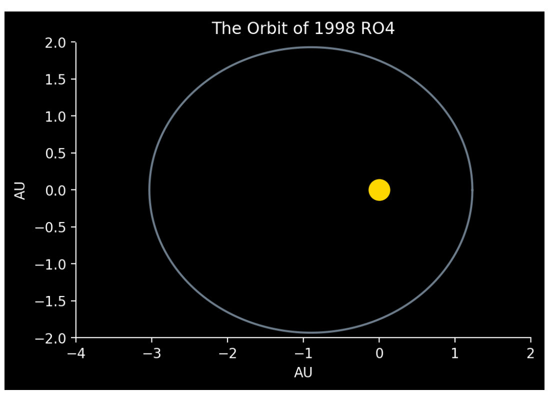

Figure 4. *This plot depicts the orbit of near-Earth asteroid 1998 RO4 (AU) in the orbital plane with the Sun at the origin.*

4. Orbital Integration

4.1. Methods

Rebound[5], a numerical integration simulation software, was used to simulate possible 1998 RO4 trajectories 50 million years into the future. The simulation program was coded in Python. Solar System bodies that have a significant gravitational influence (i.e., all of the Solar System planets except for Mercury) were added to the simulation. A 1998 RO4 particle was generated using the normal distribution curves of the previously determined 1998 RO4 orbital elements (See Section 3.2, Table 3). 60 different orbital simulations were performed.

4.2. Results

Over 50 million years, out of the 60 simulated bodies, 25.00% remained in orbit, 13.33% crashed into the sun, and 61.67% were ejected from the solar system.

5. Discussion

The orbital elements given by JPL Horizons all lie within reasonable error from our predicted values, further supporting their validity (See Figure 3). Our calculated orbital elements were derived from more recent observations, and therefore could be more accurate than JPL Horizons'. Errors determined from the consistency check were within the field of view of the telescopes, indicating that these elements are precise enough to predict the orbit of 1998 RO4.

Errors are small enough to make accurate observations in the near future, but they are unavoidable when extrapolating the asteroid's orbit to the distant future. To generate more accurate and precise elements, more instances of elements (for other distinct times) can be generated from more observations. These instances of elements could

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[5] Rebound is a numerical integration software used by the professional astronomical community to simulate the dynamic behavior of objects under the influence of gravity.

then be averaged to refine the orbital elements. Another way to reduce error would be to use a longer telescope and a CCD with higher resolution.

6. Conclusion

Telescopic images from three observation sessions were used to estimate the orbital elements and absolute H magnitude of near-Earth asteroid 1998 RO4. The method of Gauss and a Monte Carlo simulation were used to determine that 1998 RO4 has a semi-major axis of 2.130±0.009 AU, an eccentricity of 0.423±0.002, an inclination of 5.36±0.01°, a longitude of the ascending node of 191.77±0.08°, an argument of periapsis of 111.95±0.10°, and a mean anomaly on 2023 June 27 6:26:2.155 of 352.09±0.06°. Linear regression was used to ascertain that 1998 RO4 has an absolute H magnitude of 18.6. The Rebound simulation using these orbital elements showed that over 50 million years, 25.00% remained in orbit, 13.33% crashed into the sun, and 61.67% were ejected from the solar system, showing that it is improbable that 1998 RO4 will collide with Earth within this timeframe.

8. Acknowledgements

This project would not have been possible without Dr. Cassandra Fallscheer and Dr. Mike Dubson, who imparted knowledge that was essential to every step. We would also like to express our profound appreciation for the teaching assistants—Richard Qiu, Laura Zhou, Diego Rios, and Laurissa Chan, who provided valuable guidance throughout the process. Furthermore, we extend our gratitude to Ms. Sushma Bana, who organized our activities and took great care of us over the last month. In addition, we thank our peers at the Summer Science Program for providing insight and helping us understand crucial concepts for our orbital determination. Lastly, we thank the University of Colorado Boulder, Campus Manager Madison Compton, the Summer Science Program, and the Summer Science Program's affiliates and donors for providing the facilities and resources for our project.

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