Modeling Fast Moving Objects in Crowded Astronomical Neighborhoods

New Mexico

Supercomputing Challenge

Final Report

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Executive Summary

The purpose of this project is to model the motions of ‘Oumuamua (an unidentified astronomical object) as it traveled through our Solar System. ‘Oumuamua attracts the attention of astronomers due to its sudden increase in acceleration after its slingshot around the Sun. I used Gravitational Particle Dynamics (applying the force and kinematic equations) to create a model of ‘Oumuamua in the gravitational field of our Solar System. I compared this to the observed data of ‘Oumuamua’s actual motions. The model and observed data did not match, suggesting that ‘Oumuamua’s acceleration was not solely gravitational. To test other theories on ‘Oumuamua’s origins and its cause of acceleration, I applied extra forces to the model. I shall continue to add more forces in the future.

Introduction

The movements of a certain set of traveling interstellar objects can be discovered without directly observing them. One can do this by modeling the objects using Gravitational Particle Dynamics.

The object analyzed in this project is known as ‘Oumuamua. When first discovered on Oct. 19, 2017, by the Pan-STARRS1 telescope (funded by NASA’s NEOO), ‘Oumuamua was speculated to be a large chunk of metal and rock that came to our solar system by chance from the distant star Vega. [2, 10] It attracted the attention of astronomers due to its sudden increase in acceleration that occurred while it passed through the orbits of the inner planets. There are many theories as to why it did this.

The first of these theories is that ‘Oumuamua is not made of metal, but of a type of N_2 ice similar to what is found on the surface of Pluto. This theory explains ‘Oumuamua’s movements based on the non-gravitational acceleration caused by evaporating N_2 ice. Furthermore, N_2 gas is difficult to detect, and the red color and sloping surface of ‘Oumuamua are similar to that found on Pluto. ‘Oumuamua’s odd shape could be a result of mass loss the ice suffered as a result of coming too close to the Sun. [9]

A second theory is that ‘Oumuamua is a light sail, or an object that was blown by the solar winds of the sun. This theory hypothesizes that ‘Oumuamua was a comet-like object that was propelled by the Sun’s solar winds (thus explaining the anamolous accleration). [3] A question regarding this theory is whether or not the solar winds of the Sun are powerful enough to counteract the force that had caused it to travel its former course.

The third theory concerning ‘Oumuamua’s origins is that it is an alien spaceship, sent to examine the Sun. [4] A question regarding this theory is that an object moving at the rate of ‘Oumuamua may take a long amount of time to reach the Sun from another star system.

‘Oumuamua is currently difficult to directly view due to the distance between it and the Earth. I modeled it through the application of Gravitational Particle Dynamics to constrain the several theories concerning its origins.

Methods

Retrieving Data

The first step to this project was obtaining the positions of planetary objects in our Solar System. To do this, I obtained data from NASA JPL Horizons Ephemeris files [6] for the Solar System (JPL Ephemeris DE421) and ‘Oumuamua (JPL Ephemeris 3788040) and used the Python library of Skyfield [11] to calculate the positions of these planetary objects for an 80-day period in which ‘Oumuamua passed through our Solar System. The second step was to obtain ‘Oumuamua’s positions during these same 80 days. This also required the loading of an Ephemeris file using SPKType21. [12]

Effects of Gravity on ‘Oumuamua

I used this data to gain ‘Oumuamua’s initial position and velocity over the aforementioned 80-day period in the gravitational field of the Solar System. I then applied the force and kinematic equations to simulate the motions of ‘Oumuamua due to gravity. These included the equation for gravitational force ($\vec{F}$) (Equation 1), Newton’s first law (Equation 2), the equation for acceleration ($\vec{a}$) (Equations 3-4), and the equation for velocity ($\vec{v}$) (Equation 5).

$$\vec{F} = (-Gm_1m_2/r^3)\hat{r} \tag{1}$$

$$\vec{F} = m_1\vec{a} \tag{2}$$

By setting Equation 1 as equal to Equation 2, I get the result of Equation 3.

$$\vec{a} = ((-Gm_1m_2/r^3) * \hat{r})/m_1 \tag{3}$$

$$\vec{a} = \Delta\vec{v}/\Delta t \tag{4}$$

$$\vec{v} = \Delta\vec{r}/\Delta t \tag{5}$$

In these equations, t is time, G is gravity, m_1 represents the mass of ‘Oumuamua, m_2 represents the mass of each planetary object in our Solar System, and r is a position magnitude:

$$r^2 = x^2 + y^2 + z^2 \tag{6}$$

The total gravitational force affecting ‘Oumuamua is found by adding up the forces due to each planetary object. The gravitational force resulting from Equation 1 is then used in Equation 2 (Newton’s first law) to find ‘Oumuamua’s acceleration. Although m_1 is an unknown variable, it cancels out in the equation for acceleration (Equation 3), and we do not need to know it to calculate the effect of gravity.

For each day in the 80-day time period, I applied the Velocity Verlet Algorithm, as described in Equations 7 - 9. These equations are given for the x-component of the position. There are similar expressions for the y- and z-components. [7]

Solve for $x(t + \Delta t)$:

$$x(t + \Delta t) = x(t) + v_x(t)\Delta t + 1/2a_x(t)\Delta t^2 \tag{7}$$

Solve for $v_x(t + \Delta t)$:

$$v_x(t + \Delta t) = v_x(t) + 1/2a_x(t)\Delta t \tag{8}$$

Calculate $a_x(t + \Delta t)$from the gravitational force (as described in Equations 1 - 4) using $x(t + \Delta t)$.

Solve for $v_x(t + \Delta t)$:

$$v_x(t + \Delta t) = v_x(t + \Delta t) + 1/2a_x(t + \Delta t)\Delta t \tag{9}$$

The Theory of N_2 Outgassing

To calculate the effect of the outgassing of N_2, I used the rocket propulsion equations (10 - 12).

$$\vec{F} = m_1\vec{a} = \vec{v}_e\frac{dm_1}{dt} \tag{10}$$

Equation 10 is Newton’s first law, in the situation of an object (‘Oumuamua) changing in mass. The solution of Equation 10 is shown in Equation 11. [5]

$$\frac{(v(t) - v_g(t))}{v_e} = \ln\frac{m_1}{m_{1,0}} \tag{11}$$

Equation 12 gives the speed of gases that would be ejected from cometary outflows, a phenomena similar to that of N_2 outgassing.

$$v_e = -\tau\sqrt{8kT/\pi m_3} \tag{12}$$

In Equations 10 - 12, $v(t)$ is 'Oumuamua's observed speed and $v_g(t)$ is 'Oumuamua's calculated speed; $m_1/m_{1,0}$ is the mass ratio of 'Oumuamua (where $m_{1,0}$ is the initial mass); t is time; v_e is the speed of the gases that are ejected from the outgassing 'Oumuamua; T is the surface temperature of 'Oumuamua; m_3 is the mass of N_2 (which is 28 g/mol); τ has a value of 0.45; and k (or the Boltzmann constant) is 1.28×10^{23} J/K. In this calculation, τ is an efficiency factor, which is put in to compensate for the fact that N_2 gas spreads out in many different directions as it is ejected from 'Oumuamua. [9].

'Oumuamua as an Alien Spaceship

To simulate 'Oumuamua as an alien spaceship, I used rocket propulsion Equations 10 - 11 to calculate the effects of rocket boosters on a spaceship. These were exactly the same equations as were used in the calculation for N_2 outgassing, excluding Equation 12, which calculates cometary outgassing. As Equation 12 does not apply, v_e (the speed of the gases ejecting from 'Oumuamua) was assumed to be 3 km/s, a typical value for rocket propellants.

Computational Resources

To do these calculations, I used Python and the Python library Numpy, graphing the results with Matplotlib [8] and visualizing the model and data with Paraview. [1] My processor was an AMD Ryzen 9.

Results

The Velocity Verlet Algorithm and kinematic equations were used to a create a model of 'Oumumua's motions under the influence of gravity. When the created model of 'Oumuamua and the observed data taken from the Ephemeris file were placed side by side, they evidently did not match. Figure 1 illustrates the difference in position between the simulated and observed 'Oumuamua over the course of the chosen 80-day time span. This difference was calculated at each day. As the plot shows, the difference increased over time. Figure 2 displays the difference in speed between the simulated and observed ‘Oumuamua (also over the chosen 80-day time span, and also calculated at each day). The velocities in this circumstance also changed over time. Figure 3 illustrates the difference in acceleration between the simulated and observed ‘Oumuamua, which was a decrease over the 80-day period of time.

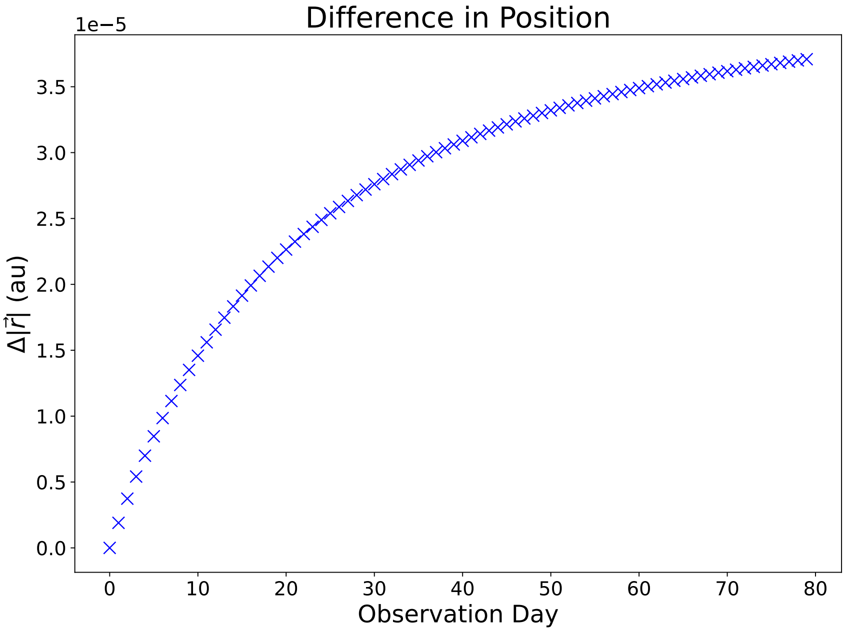

Figure 1: The difference in the positions of calculated and observed ‘Oumuamua data increased over time.

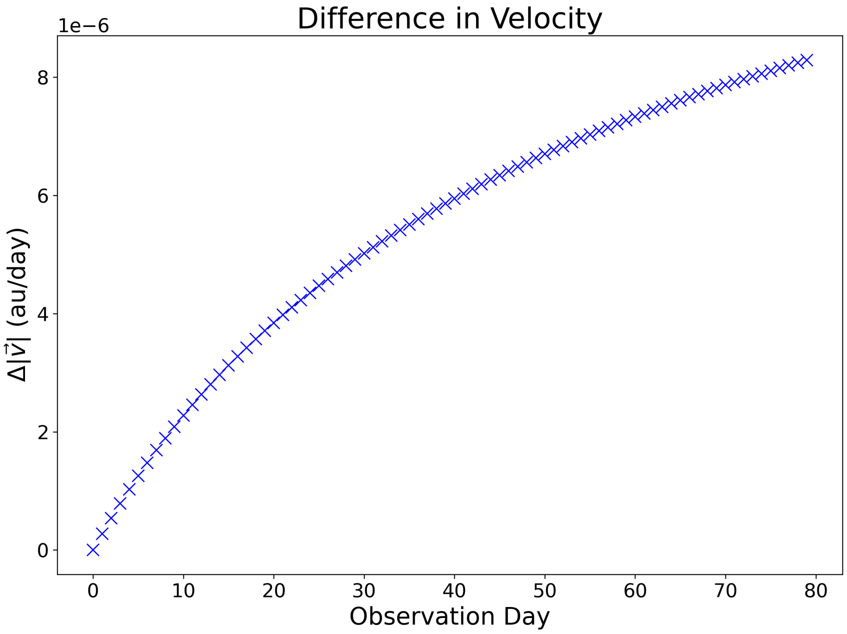

Figure 2: The difference in the velocities of calculated and observed ‘Oumuamua data changed over time.

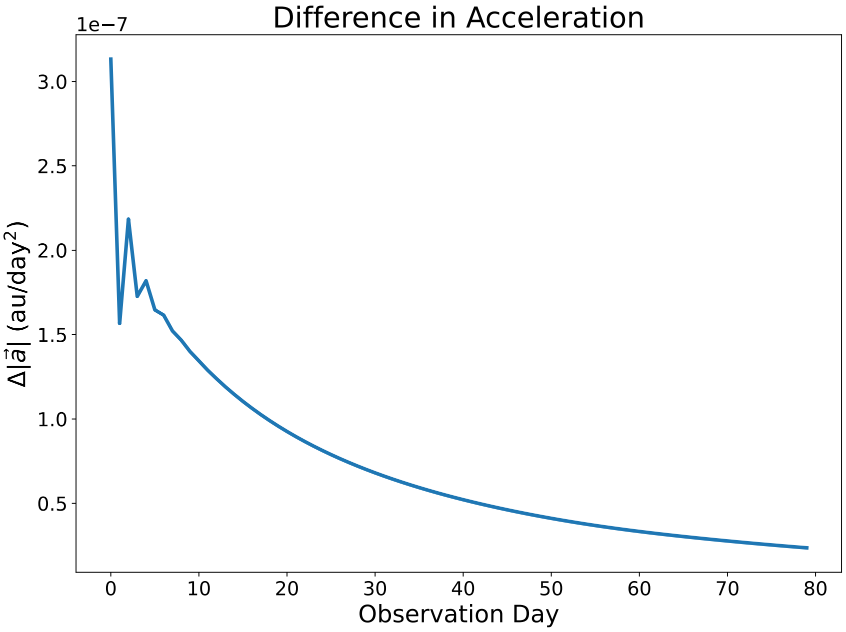

Figure 3: The difference in acceleration decreased over time.

Rocket Equation Implications

After obtaining the results portrayed in Figures 1-3, I used the rocket propulsion equations to calculate the effects of N_2 outgassing and and rocket boosters to account for the difference in speed between the observed and calculated ‘Oumuamua. The next step was to theorize which option was more likely from the calculated motions of each model force.

Figure 4 portrays the mass loss of an outgassing object over time and temperature. While an extreme change in temperature or mass and a sudden change in acceleration would suggest that ‘Oumuamua is an alien spaceship, neither of these were the case. ‘Oumuamua’s acceleration was shown to be too gradual for rocket boosters, and the changes in temperature and mass were (although still significant) relatively mild. This would suggest that ‘Oumuamua is made of N_2 ice. The model of an outgassing ‘Oumuamua that was created in the course of this project closely matched the model proposed by Jackson and Desch[9], who proposed the N_2 theory. In their model, v_e = 62 m/s, and the mass ratio is 88% (or 12% mass loss) at Observation Day 25 and a temperature of 25 K. In my calculations, the % mass loss at Day 25 and 25 K was 11.55%.

Figure 5 shows the mass loss of a rocket with boosters over time. The time was spread across 80 observation days (with an increment of one day). A rocket booster would not have used much fuel to achieve the small mass loss shown in Figure 5. The plotted results do not suggest that there was a sudden jump in mass, making it unlikely that ‘Oumuamua is an alien spaceship.

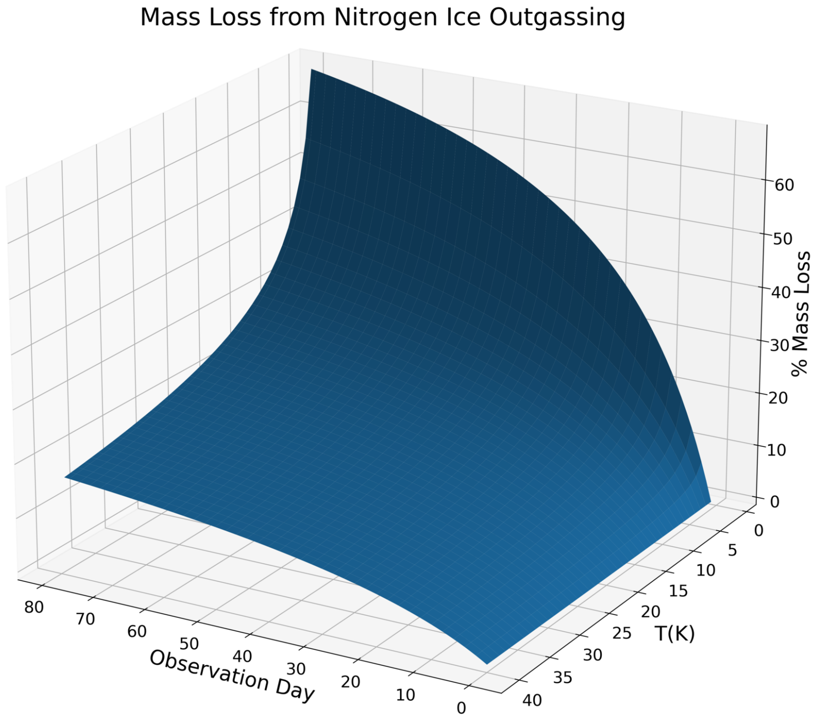

Figure 4: Calculated mass loss due to temperature (in K) over time.

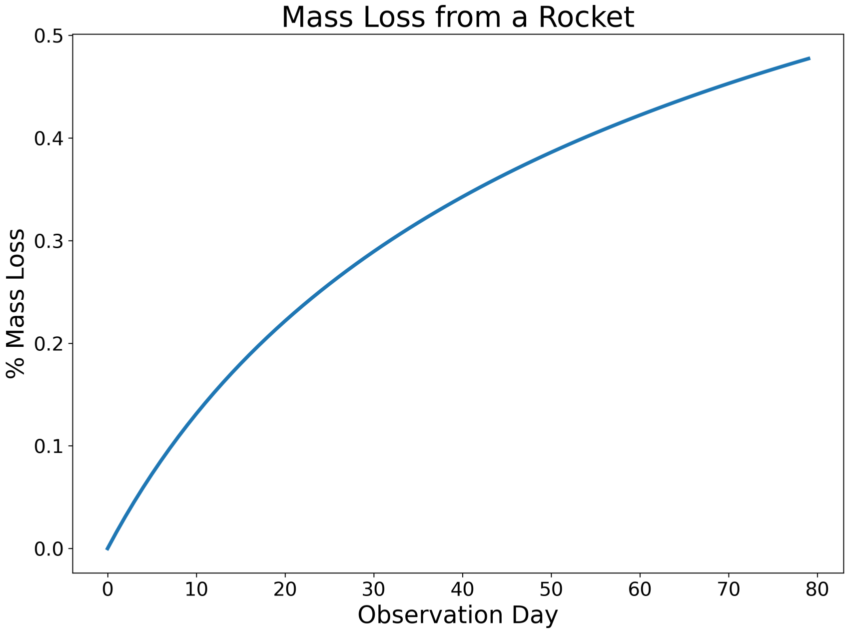

Figure 5: Calculated mass loss due to propulsion from rocket boosters over time.

Conclusions

In conclusion, the motions of the modeled ‘Oumuamua did not match the motions of the observed ‘Oumuamua; this implies that ‘Oumuamua’s acceleration was not solely gravitational. Upon applying the forces of an alien spaceship’s rocket boosters and the outgassing of N_2 ice, the model created throughout the course of this project suggests that ‘Oumuamua was most likely made of N_2 ice. To continue this project, I plan to explore the idea of another additional force that would test the light sail theory. This force would calculate the impact of solar winds on ‘Oumuamua. Should the light sail calculations disagree with the observational data, I would be able to conclude that ‘Oumuamua is most likely made of N_2 ice given the theories presented.

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