UNIVERSITY OF CALIFORNIA,
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An Analysis of Near-Earth Asteroids

W18 Intro to Python For Data Science
Final Project

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Introduction

In 1801, Giuseppe Piazzi, a priest, mathematician, and astronomer, was making a map of the sky when he noticed an unusual object moving in between the orbits of Mars and Jupiter, and named it Ceres. It was the first asteroid ever discovered, and the following year, two more were found. Today, hundreds of thousands of asteroids have been discovered, and there are telescopes around the world solely dedicated to finding and tracking them. By analyzing asteroids and their movements, we can better understand the origin and evolution of our Solar System, as well as attempt to prepare for potential impact with one.

1.1 Background

Asteroids are large rocky bodies that tend to be smaller than planets and formed in the warmer region of the Solar System, within the space known as the "Main-belt," in between the orbit of Mars and the "frost line," just before the orbit of Jupiter. After this line, planets become more gaseous and smaller bodies are more icy, like comets. Asteroids tend to take on a spherical or ellipsoidal shape, but occasionally can be irregular, like the shape of a dumbbell, or even extremely irregular, such as the "ravioli-shaped" asteroid, Pan. Both comets and asteroids that have gravitational interaction with other Solar System bodies and have the potential to enter the surrounding area of Earth are known as Near-Earth Objects (NEOs). The Jet Propulsion Laboratory's Center for NEO Studies (CNEOS) was created from NASA's Planetary Defense Coordination Office to assess the trajectories of these comets and asteroids, and encourage ideas about methods to deflect them. In this report, we explore several key aspects of asteroids: Tholen/SMASS spectral type, 2D/3D plots of eccentricity, inclination, and semi-major axis, size of asteroid based on grouping in the Solar System, and oribital period as a function of distance from the Sun.

1.2 Dataset

We utilize data from the Small-Body Database (SBDB) organized by the Jet Propulsion Laboratory, a national research facility operated by the California Institute of Technology. Our dataset contains characteristics about both near-earth and potentially hazardous asteroids, which help us understand their formation and evolution, possibly around similar type stars as well. The search engine gives the user the ability to filter by parameters like object type, and physical and orbital characteristics, such as whether it exists in the Main-belt, which will be discussed later. For our purposes, we narrowed the search to basic and physical (much harder to determine) characteristics of only asteroids, and use a resulting .csv file with approximately 990,040 rows and 25 columns.

The following are common fields used to describe Solar System bodies that we use for analysis:

- i: measure of inclination, or how far above or below object is from the ecliptic plane (in degrees)

- e: eccentricity is a measure of how much an elliptical orbit deviates from a circular orbit (unit-less)

- a: the semi-major axis in Astronomical Units (AU), or the distance to object from the Sun

- q: perihelion distance in Astronomical Units (AU), the distance when the object is closest to the Sun in its orbit

- Q: aphelion distance in Astronomical Units (AU), the distance when the object is farthest to the Sun in its orbit

- H: absolute magnitude, or how bright the object is from a designated distance (unit-less)

- Diameter: approximate length (often average length due to irregular shape) of the object if known (in kilometers)

- P: the sidereal orbital period (in years), which is how long it takes for the object to complete one orbit around the Sun.

- w: argument of perihelion (in degrees), or the angle

- data-arc span: number of days spanned by the data-arc (days)

- num obs: number of observations of the object (unit-less)

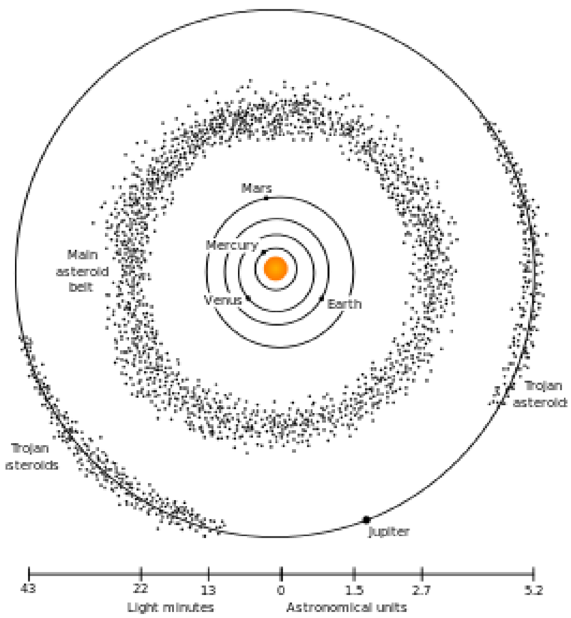
- albedo: factor of how well object reflects light (unit-less)

- rot period: how long it takes object to rotate about its own axis (in hours)

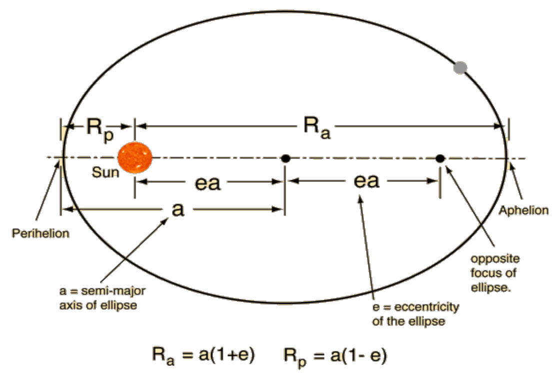
- GM: gravitational parameter- the mass of the object multiplied by the gravitational constant (km^3/s^2)

- B-V, U-B, I-R: color indexes for magnitude difference. Asteroids observed in multiple wavelengths (unit-less)

Not all of these fields in the dataset are of interest for the scope of this project, so we drop these as well as some additional columns. We use the pandas and numpy packages to read in the .csv file, convert to a dataframe, and filter and group the data to see where the largest clusters of the asteroids reside, and what kinds of asteroids are most prominent, discussing factors like orbital features and brightness. We also use the matplotlib and sklearn packages to create the histograms and plots included. We will compare some results with previous findings to see what kinds of trends exist for known asteroids and discuss what factors are still unknown. This project only covers a small fraction of the study of Near-Earth Asteroids, and many aspects or further exploration is not included in the scope of the project in the interest of time.



(a) Diagram of asteroid belt locations



(b) Elliptical orbit components. Here, Rp is equivalent to 'q', and Ra is equivalent to 'Q'.

Figure 1.1: Asteroid Orbital Components

Chapter 2

Brightness and Composition

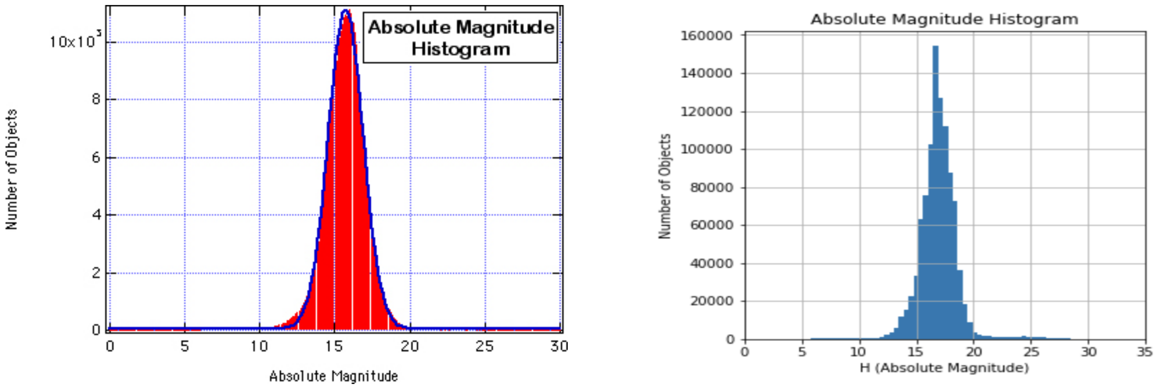
Knowing the way an object absorbs and reflects light is a clue to its composition. Because astronomers observe so many celestial objects of various distances and sizes, they created the absolute magnitude to define a logarithmic scale of luminosity for an object, as if you were looking at every object from 10 parsecs, or 32.6 light-years away, without any other source of interference or dimming factors in the way. The star Vega is used as the main reference point for this scale and has an absolute magnitude of 0. The smaller the value, the brighter an object is.

$$d = 10^{3.1236-0.5log10(a)-0.2H} \tag{2.1}$$

where 'H' is absolute magnitude, 'a' is albedo, and 'd' is diameter (Bowell et al.). These means that for larger asteroids, we expect them to be brighter because they are able to reflect more light. Knowing the brightness and size of an asteroid is very effective in understanding its origins and what it may comprised of.

2.1 Albedo

Albedo is the innate brightness of the object, or its ability to reflect light, with a value of 1.0 being a purely-white, reflective surface, and 0.0 being a black non-reflective one. In 2006, Lowell Observatory in Flagstaff, AZ, did an analysis of asteroids as well, and even though at that time the analysis was done for only 336,341 asteroids, we find a similar result for the asteroids in this dataset, shown in Fig 2.1 ("The Asteroid Orbital Elements Database", Lowell AstorbDB). Though the distribution appears very Gaussian, in reality it is probably more exponential since there are more small than large asteroids, and there is a bias towards brighter ones since they are easier to detect.



(a) Absolute magnitude histogram from Lowell Observatory data, circa 2006

(b) Absolute magnitude histogram from current data

Figure 2.1: Absolute magnitude histograms of asteroids

2.2 Spectral Type

The taxonomy for asteroids was first proposed by David Tholen in 1984 with 14 types after doing a survey of asteroids in 8 different colors and combining them with their albedos. The SMASS (Small Main-Belt Asteroid Spectroscopic Survey) classification was an effort in 2002 to sort the types even further by doing higher-resolution observations of the asteroids in various wavelengths, which ultimately re-grouped them into 24 types, with C, S, and M being the 3 main categories, though some NEO's did not fall into these typical categories. By observing these asteroids in different wavelengths and taking spectra, we can see which wavelengths of light are being absorbed or reflected, giving an indication of what the asteroid might be comprised of. While there are at least 8 different types, the majority of asteroids fall into 3 categories: C-Type, S-Type, and M-Type. C-Types are most common, and found in the outer regions of the Main-belt. They tend to be very dark, and their compositions are carbonaceous, often with depleted Hydrogen and Helium. About 75% of asteroids fall under this category. S-Types, which are much brighter and found in the inner belt, tend to be made of iron and manganese silicates. Only about 17% of asteroids are S-Types. The last main group is M-Type, which are found in the middle region of the Main belt. We filtered the dataset only by rough-estimate albedo ranges as part of the scope of this study. C-types are very dark with an albedo of 0.03-0.09, S-types are relatively bright with an albedo of 0.10-0.22, and M-types are also relatively bright with an albedo of 0.10-0.18 ("Asteroids", NASA). A more accurate classification dichotomy is recommended for determining the exact type the asteroid falls into. We found 73,867 that were C-Type, 32,612 that were S-Type, and 24,324 that were M-type, which roughly correlates with expected distribution, in Figure 2.2.

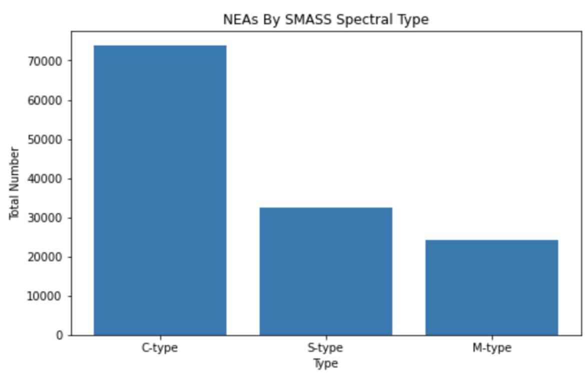


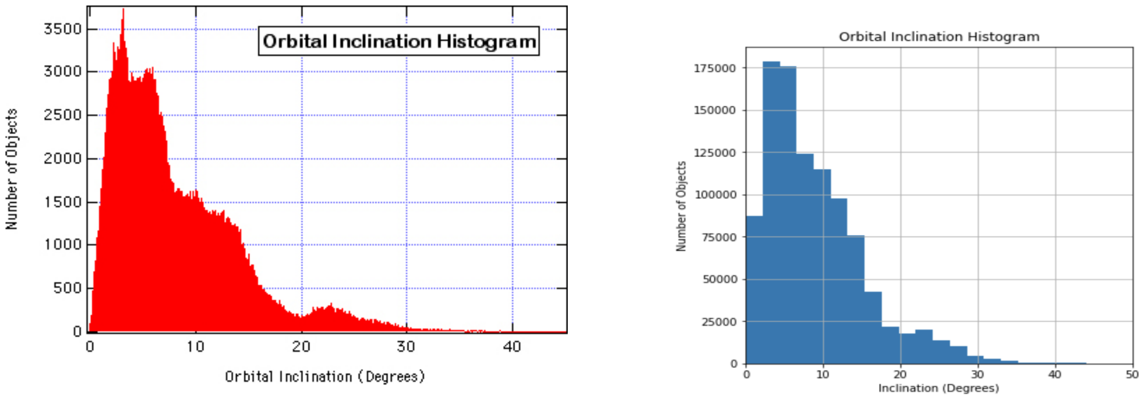
Figure 2.2: Asteroids by SMASS Classification

Chapter 3

Size & Orbit

The true size of asteroids is difficult to constrain due to the limited direct observing techniques astronomers use. The most common are resolving images with adaptive optical systems or radar, observing with space-based telescopes, and waiting for an asteroid to pass in front of a star. These work best for bigger asteroids or those with orbits closer to Earth. However, with several indirect techniques like polarimetry, one can find an albedo and absolute magnitude, which combined can be used to find an effective diameter. Even though there are a great number of asteroids, because of their small nature, it's thought that even if they were all combined, they would only make up an entity about half the size of Earth's moon. However, small in nature does not necessarily mean innocuous in nature, as we have seen with historical events on Earth, such as the Chicxulub impact that wiped out the dinosaurs, thought to be no more than a few miles wide. By understanding the orbits of these small but deadly bodies, we can understand how they behave and if one has the potential to pose a similar threat in the future. Several of the key elements of an orbit are eccentricity, the semi-major axis, and the inclination. For the most part, objects in the Solar System tend to have more circular orbits (e ¡ 1) and the planets tend to have little to no inclination. For asteroids specifically, they also have quite circular orbits, and they tend to be grouped at around the 2.8 AU mark and 5.2 AU mark, where the asteroid belts are. Bodies like planets accreted matter onto them in the form of ice, rock, dust, and gas, and the asteroids we see today are remnants of that era. Many believe that most of the asteroids left over did not successfully accrete onto Jupiter in the formation process of the Solar System nearly 4 billion years ago. Jupiter has the biggest gravitational influence in the Solar System next to the Sun, which is why these asteroids still remain close to its orbit. Once again, when breaking down the dataset by orbital features, and comparing them to 2006 Lowell observations, we find a similar result in Figures 3.1 and 3.2.

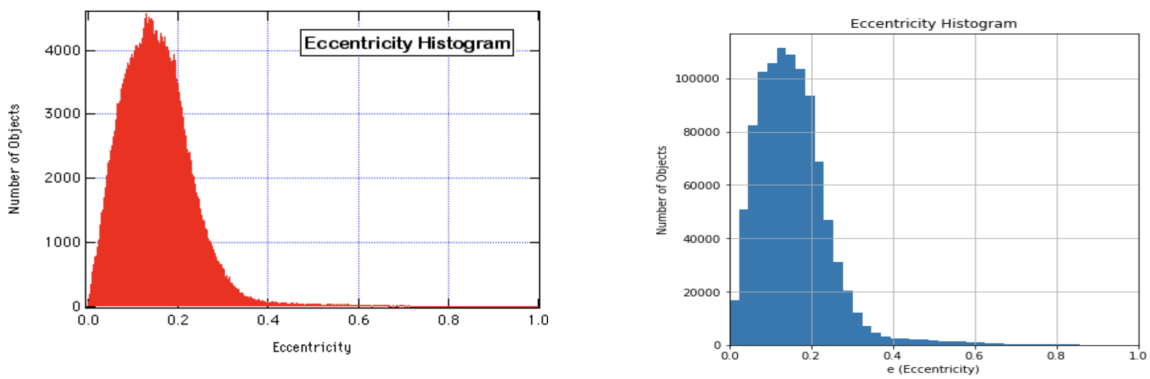
In addition to the distributions for each orbital feature, we also compare them to each other to better understand their influence. Dynamically, we would expect an object at a further distance from the Sun to have less of a gravitational pull and take longer to make a full orbit, which appears to be the case in Figure 3.4. It is interesting how many objects at further distances have shorter orbital periods than expected, and warrants further investigation. In Figure 3.3, we can see that as expected, the majority of the asteroids tend to have quite circular orbits with eccentricities under 1, even as you go further out in distance. But unlike the planets, we can see that asteroids have vastly different inclinations, ranging from flat, to vertical, to diagonally opposite. This is one key factor that actually helps astronomers determine what are planets, dwarf planets, or other bodies.



(a) Inclination histogram from Lowell Observatory data, circa 2006

(b) Inclination histogram from current data

Figure 3.1: Inclination histograms of asteroids



(a) Eccentricity histogram from Lowell Observatory data, circa 2006

(b) Eccentricity histogram from current data

Figure 3.2: Eccentricity histograms of asteroids

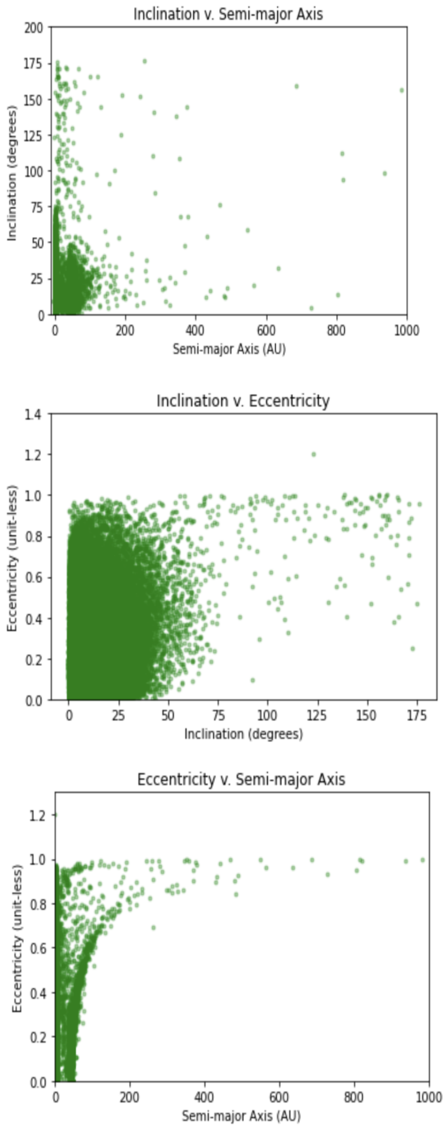


Figure 3.3: Eccentricity, Inclination, and Semi-major axis comparisons

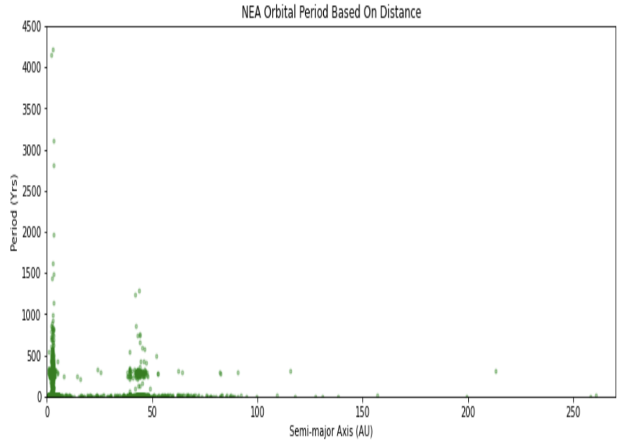


Figure 3.4: Orbital Period by Distance from the Sun

3.1 Special Orbits

There are several main categories that some asteroids fall into: Amors, Apollos, Atens, and Atiras. These categories contain asteroids with special orbital behaviors and are named after the first asteroid found with the observed behavior, shown in Figure 3.4. In the dataset, of the total 23,174 NEA's present (2.3% of the all known asteroids), by filtering by the appropriate aphelion, perihelion, and semi-major axis parameters, 12,812 are found to be Apollos (1.3%), 8,584 are Amors (0.87%), 1,754 are Atens (0.2%), and 23 are Atiras (0.002%), shown in Figure 3.2. These asteroids were most likely either gravitationally pulled into the Solar System, or thrown out from another body rather than forming with the larger majority of asteroids in the Main-belt and Trojan areas.

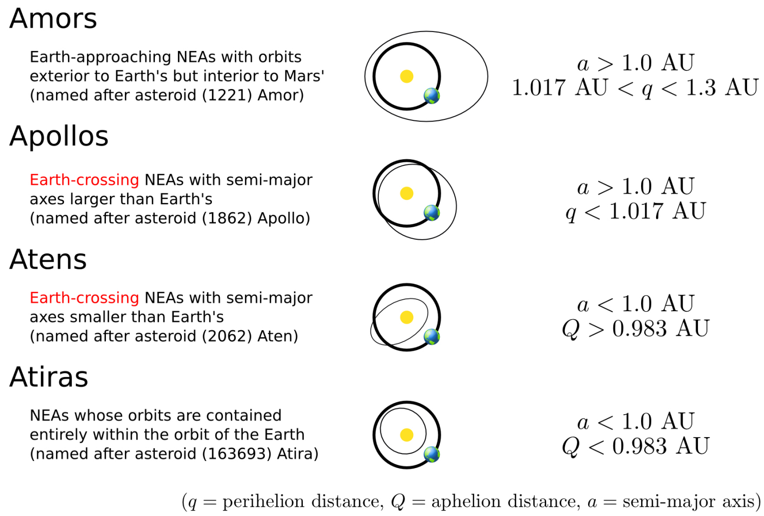


Figure 3.5: Asteroid orbital classifications based on perihelion, aphelion, and semi-major axis

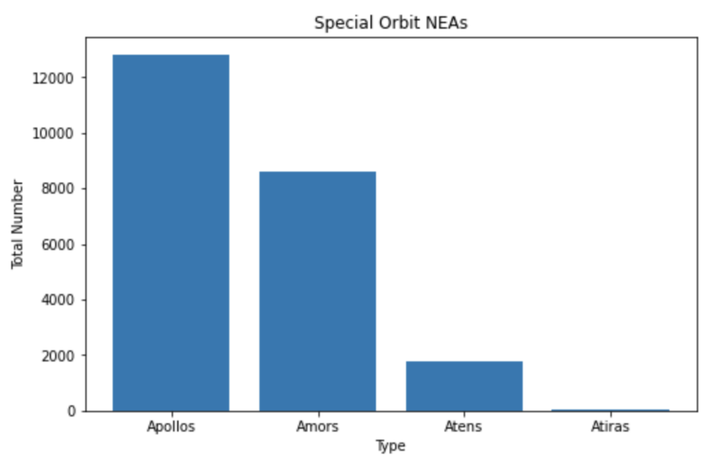


Figure 3.6: Number of special objects by category

3.2 Size

Asteroids have a variety of shapes and sizes, which are usually determined by where and when they were formed. We looked at where in the Solar System the smaller and larger asteroids tended to be located. For this particular subset, we had to filter the dataset to those asteroids where the diameter is known, which is actually only about 14% of the data, due to difficulty of direct observation and low albedo. Nevertheless, it's clear to see that for the most part, looking at the asteroids within the surrounding 10 AU radius, the ones grouped in the Main-belt tend to be smaller than those further out in the Trojan belt closer to Jupiter, as shown in Figure 3.7.

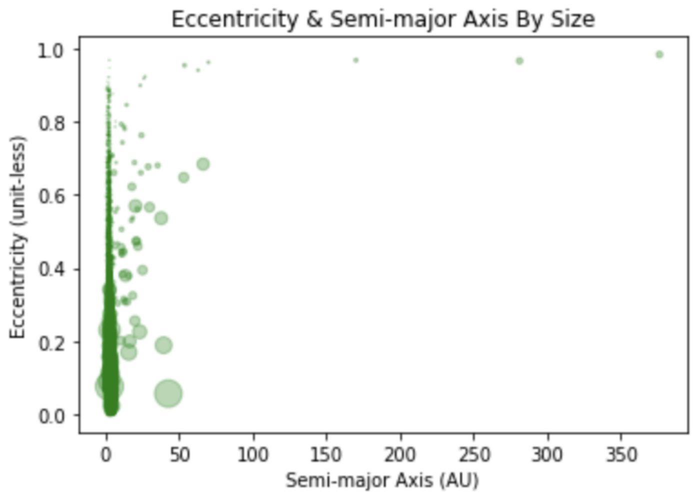


Figure 3.7: Asteroid size based on distance from the Sun

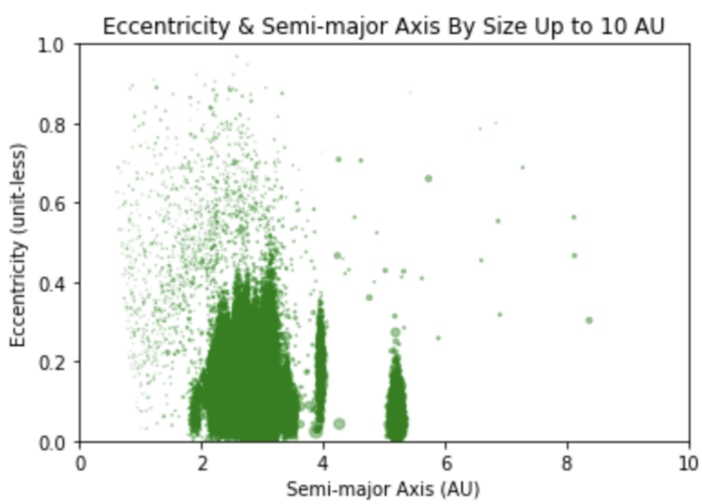


Figure 3.8: Asteroid size based on distance from the Sun up to 10 AU. Increase at 2.8 AU and 5.2 AU, where Mai-belt and Trojan belts are respectively.

Chapter 4

Conclusion

Approximately 900,039 asteroids have been discovered since 1801, and there are still many we expect have yet to be confirmed. As shown in this study of NEO's, these asteroids may be small in nature, but with just the right orbital parameters, could be devastating for a planet like Earth. In some ways, they share a lot of the same characteristics of our planet: circular-ish orbits, sometimes reflective, and may even contain similar compounds, which is no surprise considering they were formed around the same time. But in other cases, asteroids can be much more unexpected, with orbits having vastly varying degrees of inclination, large rogue bodies that don't follow trends, and several that have compositions that don't quite make sense. Studying these things, as well as other aspects of asteroids not covered in the scope of this project, provides a window into the origins of the Solar System, and sometimes even beyond in the case of the first asteroid in the dataset, Oumuamua, the only known asteroid to come from outside the Solar System. It also may give us time to discover a way to deflect one. Asteroids also serve as a potential resource, should technology rise to meet the occasion. Therefore discovering, confirming, and monitoring asteroids, and constraining their parameters is essential to astronomy, and the well-being of Earth itself.

Chapter 5

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