# 1. INTRODUCTION

## 1.1 Asteroids

The discovery of celestial bodies and our solar system increased over the year, and that was extended to the region beyond Neptune, where there lies the Kuiper belt. The Kuiper belt was hard to determine the celestial body character to determine the distinctions of these bodies. Therefore, the International Astronomical Union (IAU) resolved in the year 2006 that better explained the distinct characters of planets to other bodies. Our solar system’s three main distinct bodies include planets, dwarf planets, and small solar system bodies [ref].

A planet is a celestial body characterised by its orbit around the Sun (the orbit being elliptic with the Sun on one of its foci). The planet also has its own sufficient mass for a sustainable gravity that cannot be manipulated by other rigid body forces emanating from other celestial bodies. And that a planet has a cleared vicinity in its orbit. On the other hand, a dwarf planet is also a celestial body that does orbit the Sun and has sufficient mass to overcome eternal rigid body forces due to its gravity. The self-gravity phenomenon is what makes both a planet and a dwarf planet have a spherical or rounded shape. Where Dwarf planets differ from planets is that they do not have a cleared vicinity in their orbit. And lastly, they are not satellites like the moon.

Therefore, all the remaining objects in the solar system, except for the Sun and other satellites, are referred to as small solar system bodies. Going by this name, both asteroids and comets are included in it. The distinct feature between the two is the material composition that most asteroids consist of either metal or rock. At the same time, comets are made up of water ice (that starts to evaporate upon approaching the Sun creating the tail) and dust particles.

A screenshot of a computer

Description automatically generated with medium confidence

Figure ‑ Asteroids in our solar system. [ref]

Asteroids are small rocky bodies orbiting the Sun. They are sometimes called minor planets. According to NASA, asteroids are:

*“Rocky remnants left over from the early formation of our Solar System about 4.6 billion years ago.”*

There are currently 1,097,106 known asteroids, says NASA. Asteroids are different from meteors, which are small bodies of matter that appear as a streak of light when entering the Earth’s atmosphere [ref]. Asteroids are celestial objects that can be found in our solar system and have unique features since their discovery has been a pivotal study to the formation of our solar system. In 1801, the first asteroid to be discovered was Ceres (later named a dwarf planet) by Guiseppe Piazzi [ref]. Guiseppe was an Italian priest, a mathematician, and an astronomer. One of his establishments was the *Osservatorio Astronomico di Palermo*, an observatory located in Palermo, Italy. Years passed, and the rise of more new discoveries was made. These discoveries and observations have continued to help better understand the space environment, the material composition of asteroids, their orbit, and orbital elements.

A diagram of the moon

Description automatically generated with low confidence

Figure ‑Asteroid scales from largest to the smallest. [ref]

The encyclopedia of the solar system [ref] defines an asteroid as being a rocky carbonaceous or a metallic body, ranging from few meters to a thousand kilometres, and orbiting the Sun. They are also referred to as minor planets. Thus, the organization, Minor Planer Centre (MPC), was formed to bring about the study and cataloguing of asteroids [ref]. Not all asteroids are solid bodies; ones with a small diameter of fewer than three hundred metres are rubble piles [ref]. Studies on asteroids are crucial to learning properties such as orbital characteristics, rotation speed, age and colour, material composition, mass, and size. Such properties are used in astronomical research, and one main consequence of these properties is the actual formation of the planetary system[ref]

## 1.2 NEO

NEOs comprises both asteroids and comets with a perihelion distance of less than 1.3 AU (Astronomical Unit). The difference between the asteroids and comets is that the Near-Earth Comets (NECS) have short periods with an orbit period of fewer than two hundred years. As for asteroids, they are grouped as NEAs (Near Earth Asteroids) based on their orbit elements, as explained in section 1.3, comprising of the Atira, Aten, Amor, and Apollo. The other group of asteroids are the Potentially Hazardous Asteroids (PHA) which have two parameters, the absolute magnitude (H) and the Earth Minimum Orbit Intersection Distance (MOID). These two parameters are useful to determine any approach of these asteroids to Earth and collision. As mentioned in section 1.1, the study collision of asteroids provides information for planetary formation and Earth’s origin. They also stand a chance to collide with Earth, destroying the planet or extinction of life with the dinosaurs [ref]. Therefore, it is important to know as much as we can about these asteroids.

Table : NEA groups and their properties. (q = perihelion, Q = aphelion, a = semi-major axis, and P = period) [ref]

|  |  |  |
| --- | --- | --- |
| **Group** | **Definition** | **Description** |
| NECs | q<1.3 [au](https://cneos.jpl.nasa.gov/glossary/au.html) P<200 years | Near-Earth Comets |
| NEAs | q<1.3 au | Near-Earth Asteroids |
| Atiras | a<1.0 au  Q<0.983 au | An Atira orbit is contained entirely with the orbit of the Earth (named after asteroid 163693 Atira). |
| Atens | a<1.0 au  Q>0.983 au | An Aten has a semi-major axis smaller than Earth’s (named after asteroid 2062 Aten). |
| Apollos | a>1.0 au  q<1.017 au | An Apollo has a semi-major axis larger than Earth’s (named after asteroid 1862 Apollo). |
| Amors | a>1.0 au  1.017<q<1.3 au | An Amor has its orbit exterior to Earth’s and interior to Mars’ (named after asteroid 1221 Amor). |
| PHAs | MOID<=0.05 au  H<=22.0 | PHAs are NEAs whose (MOID) with the Earth is 0.05 au or less and whose absolute magnitude (H) is 22.0 or brighter. |

The Earth MOID has a minimum distance between their orbits to Earth. This is useful to study the approach of these asteroids to Earth. The PHAs are identified as Earth MOIDs having less than or equal to 0.05 AU. Therefore, these earth MOID signal a high risk of collision. It is necessary to track and observe these PHAs as the Earth’s gravitational perturbation. Because these asteroids tend to change their orbit with time, affecting their semi-major axis over time. [ref]

The tracking and observation are done by observing the brightness of the asteroids using the H parameter. This brightness is a measure of the Sun’s rays bouncing off the surface of the asteroid as seen from Earth. H can be used to determine the diameter of the asteroid based on the equation [ref]:

Where *a* is the albedo of the asteroid. The diameter can then help create a taxonomy of PHAs with a higher H of about twenty-two if their diameter is more than 140m. Therefore, such asteroids would be marked as PHAs. But with the understanding of H and diameter, other mechanisms help understand the origin of these NEAs as most came from the MBA (Main Belt Asteroids). The collision of asteroids in the Main Belt would result in a part of the whole asteroid moving to a new gap in the belt. This is because of the Kirkwood gaps [ref]. Several zones of low density in the minor-planet population were noticed about 1860 by Daniel Kirkwood, an American mathematician and astronomer, who explained the gaps as resulting from perturbations by Jupiter. The Kirkwood gaps make asteroids absorb and reradiate the sunlight rays that hit an incidence angle to the surface as it revolves around the Sun and rotates about its axis. The process tends to modify the asteroid’s orbit with time. If an asteroid shifts into one of the Kirkwood gaps, its orbit gets perturbed from Jupiter’s gravity, increasing the orbit’s eccentricity. Over time, the asteroid has a closer approach to planets, from Mars and later Earth’s orbit. At this point, this asteroid becomes a NEA. If further perturbations cause the eccentricity to lower, the NEA will always be near Earth’s orbit.

Secondly, asteroids with a diameter no more than 18km would have a progressive movement around their orbit for millions of years caused by the orbit resonance with the planet Jupiter, creating a resonance movement that is caused by the Yarkovsky effect. It describes a small but significant force that affects the orbital motion of meteoroids and asteroids smaller than 30-40 kilometers in diameter. It is caused by sunlight; when these bodies heat up in the Sun, they eventually re-radiate the energy away as heat, which in turn creates a tiny thrust. This recoil acceleration is much weaker than solar and planetary gravitational forces, but it can produce substantial orbital changes over timescales ranging from millions to billions of years. [ ref]. The effect comes into play when an asteroid has a prograde motion, as it accelerates the asteroid further away from the Sun. The opposite happens if the asteroid has a retrograde motion, reducing the asteroid velocity and moving closer to the Sun.

## 1.3 Discovery of asteroids

The discovery of asteroids and NEOs is increasingly important and becoming mainstream. Most astronomers would observe these asteroids using telescopes at their homes and share their data with the MPO. More powerful telescopes and associations/organisations like MPO provide object data catalogues and datasets which the public can access. In the recent asteroid day held on June 30, 2021, the European space agency accounted that over 26000 NEAs have been observed so far. [ref]

Among the discovery, surveys include the NEO-Wise, which covers and observes a wide span of the sky every night. These telescopes used a high field of view (FOV) to detect moving objects as stars remain still in the background. The moving objects mostly are asteroids but can also be a comet. The discovery observation can account for existing and discovered asteroids to newly and undiscovered ones, potentially impacting Earth if not well studied or detected earlier.

The data developed by the MPC is then shared among astronomers who can perform analysis and photometric studies of these asteroids and the newly discovered ones. It is important to create a streamlined follow-up analysis and observations to accurately determine the physical properties of the asteroids, one of them being the rotational period. Other features include the surface material composition, albedo, shape and size and orbital elements. More observations are made frequently as uncertainties develop with the asteroids that can affect many physical properties.

During observations, biases are bound to appear, especially when trying to discover objects that are NEO. Orbital elements such as low inclination and eccentricities are helpful in the detection of NEOs. Another useful observation moment of NEOs is during the winter solstice, especially from November to January. The reason is that during this period, the nights are longer in the northern hemisphere, and thus, more time can be used to observe the asteroids. Most of the observatories and powerful telescopes are in these regions. [ref]

The table below shows the group of NEOs and their corresponding semi-major axis and perihelion. The Atira orbit is much closer to Earth’s orbit than the rest of the family of NEOs. Apollos are far outside the Earth’s orbit while the Aten and Amor groups cross Earth’s orbit from time to time. Most of the NEOs are the Apollos and Amors that make up most of the NEO population. [ref]

## 1.4 Photometry and Light Curve

Information and data from astronomical activities come in the form of electromagnetic radiation. This radiation has a wide range of wavelengths. Therefore, analysing each range of the electromagnetic spectrum can provide useful information such as material composition on the surface, temperature, amongst others [ref]. In the optical region, one can see those stars and galaxies that emit a large amount of energy. One can see that the Earth’s atmospheres are transparent to some degree. These two observations have led to the photometry technique that has become a key observation in astrophysics [ref]. Since asteroids emit the energy from the Sun hitting the surface, it is possible to observe asteroids using photometry.

Photometry is the scientific study of measuring the variation of an asteroid brightness from its rotation around its spin axis [ref]. It is the science of measuring the amount of energy released by a celestial body over a designated wavelength band of radiation [ref]. This amount of energy is then termed flux or brightness. After the photometry analysis, a light curve is then created, which is a tie-series of an asteroid’s brightness. It is a plot of the data observed from the asteroid on the scale of magnitude. Therefore, the brightness computation caused by the object’s rotation and finally analysing that data is termed light curve photometry [ref]. The light curve scale has a phase that marks a complete rotation of the asteroid around its axis. Thus, astronomers can determine the rotation period based on the phase. Since most asteroids have a constant albedo and that their shape appears not to be symmetrical. The phase goes from 0 to 1, confirming a complete rotation of the asteroid as is given by equation (2) here is the initial time chosen as the first measurement in the dataset. is the rotation period.

As mentioned earlier, the magnitude of the asteroid fluctuates over time while rotating. And since rotation is a periodic event, this would result in a change of magnitude. Thereby, the rotation period can be obtained from the light curve and a fitting method to find the most accurate period. The process involves first observing the asteroid at various periods of the night to determine its apparent magnitude. The telescopes aim at different parts of the sky to firmly position well with the asteroid. The FOV is larger to see other catalogued stars in the images to know the exact point and position of the asteroids in their orbit. Most pictures are taken using a V-filter, where the V stands for *“Visual”,* which is part of the visible electromagnetic spectrum [ref]. Astronomers relate it to the CCD asteroid flux to the apparent magnitude and compare it to the CCD flux of the catalogued stars in the background. Many pictures are taken per night over a specific duration of days that will determine the asteroid’s apparent magnitude on those various days.

The period of asteroids can range from those having less than two hours of rotation to those that take up from several days up to two months. Asteroids with a much shorter rotation period have a rate below which their centrifugal force would result in a rubble pile flying off against its gravity, regardless of size. Such asteroids do indeed have a solid composition of the material, which contradicts the possibility of the rubble pile structure of asteroids. This is a scientific mystery that has not been found and solved yet. The asteroids with slow rotation periods have unclear origins. Over the years, more data is gathered from them further to understand the reason for their lengthy rotation periods. [ref]

Finally, the importance of light curve study determines correlations between the rotation period, taxonomy class, size, location in the belt or its orbit and orbit propagation. Also, it can help in shaping the asteroid and finding pole orientations of the asteroid.

## Orbit determination

## Scope of work

### Objectives

The objective of the thesis is to determine the rotation period of the NEAs. The motivation of this research is the effort and research work that is dedicated to understanding the physics and dynamics of NEAs and better predicting collisional events with Earth. Each day these NEAs have their orbits and dynamics changing due to Kirkwood gaps and the Yarkovsky effect, amongst others. Therefore, the work presented in this thesis is an empirical study and determining the most accurately rotation period of the selected NEAs. The research also seeks to answer the question:

*“What approach can we use to determine the rotation period of NEAs?”*

The question further expands on the initial processing of the data and how to output the light curves. The dissertation aims to develop and use methods to process the datasets and compare the MPC output light curves. There are six NEAs in this study, and they include IVAR 1627 (Amor), 1998 TU3 (Aten), 2000 QL7 (Amor), 2001 SG276 (Amor), 2001 UY4 (Apollos) and 2003 RP8(Amor).

### Outline

The thesis outline is as follows:

1. Chapter 2 contains an in-depth literature study that involves studying the asteroids and the various belts that contain them. After that, a study on how various techniques are used to study, including radiometry, spectroscopy, and photometry. Photometry is then broadly explained with each party of the analysis and process presented. This then offers the importance of why we study the rotation periods and how to present them. And finally, the chapter concludes with modelling and software used to process asteroid data.
2. Chapter 3 introduces the methods that shall be used in the project. It also introduces the databases where the NEAs datasets are obtained.
3. Chapter 4 offers a step-by-step approach on how to process and analyse the photometry of each of the NEAs. It starts with acquiring the datasets from the databases of ALCDEF and MPC, then processing one of the NEA’s images. Finally, the photometry measurements are done, and finally, the light curves can be made. Then, the preliminary orbit determination process is next with a step procedure from acquiring the state vectors and time and steps to obtaining the orbital elements.
4. Chapter 5 shows each NEA’s light curves, and a periodogram and analysis are made for each of them. Then the orbital elements of each NEA are presented with a comparison of the values from the MPC. Finally, orbit plots are created.
5. Chapter 6 concludes the thesis with remarks to the dissertation and possible future work that investigates new techniques used to obtain the rotation period.
6. The appendix has further derivations of the equations involving the methods used for the initial orbit determination.