Asteroid Tracking
Introductory Guide

Background

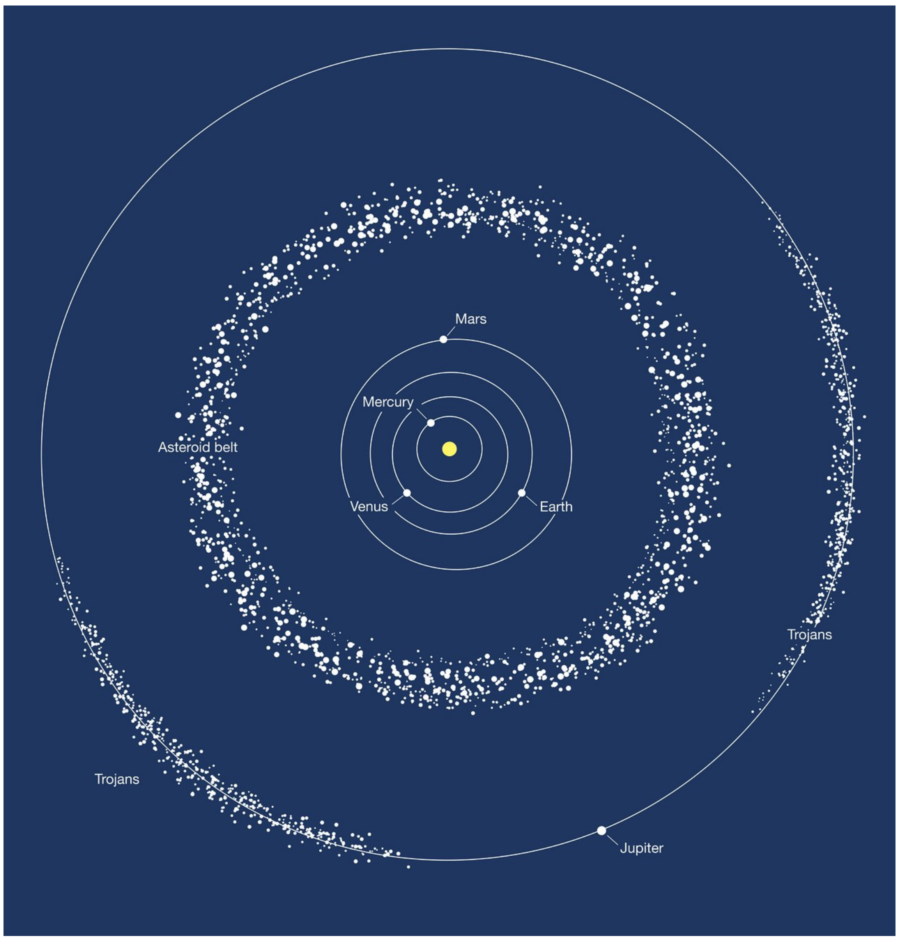
Our solar system contains millions of asteroids and comets. These objects are leftover material from planet formation at the birth of our solar system when particles of dust, rock, and ice gradually coalesced to form the major planets we know today. Asteroids are composed primarily of rock and metal elements, whereas comets contain large portions of water, methane, and ammonia ices in addition to rocky material mixed in. For this reason, comets often spout large, characteristic tails as they approach the Sun and ices vaporize off their surfaces, whereas asteroids do not produce tails.

Asteroids are commonly referred to as minor planets. They are called minor planets because they orbit the Sun, just like the "major" planets, but they are much smaller and more numerous. When someone refers to a minor planet, they are referring to any small object orbiting the Sun that is not a comet, but could have a wide range of origins and compositions.

The asteroid 433 Eros (left) was visited by the *NEAR Shoemaker* space probe in 2000. The comet 67P/Churyumov-Gerasimenko (right) was visited by the *Rosetta* space probe in 2014.

Many people know that our solar system has an asteroid belt, which is an area between the orbits of Mars and Jupiter that contains a great number of asteroids. In contrast to the depictions of asteroid belts in movies like Star Wars, the density of asteroids within the belt is actually still pretty low. In fact, the average distance between asteroids within the asteroid belt is over 100,000 miles - it would hardly be a challenge to fly the Millenium Falcon through it!

What is less well known is that our solar system contains many different "belts" or groups of minor planets and comets. The orbital characteristics of each of these minor planet populations is the basis for classifying minor planets into groups. Some famous asteroid groups include the Jupiter Trojan asteroids, which follow Jupiter behind or ahead of its orbit as they are trapped in Jupiter's gravitational zone of influence. There are also Earth-crossing asteroids (any asteroid that crosses Earth's orbit), which itself is broken into many smaller groups, and the Kuiper belt, which has a massive population of both comets and asteroids out past the orbit of Neptune. For reference, Pluto is considered to be a dwarf planet within the Kuiper belt group, part of why it is no longer considered a "major" planet. These are just a few of the different minor planet groups that exist.

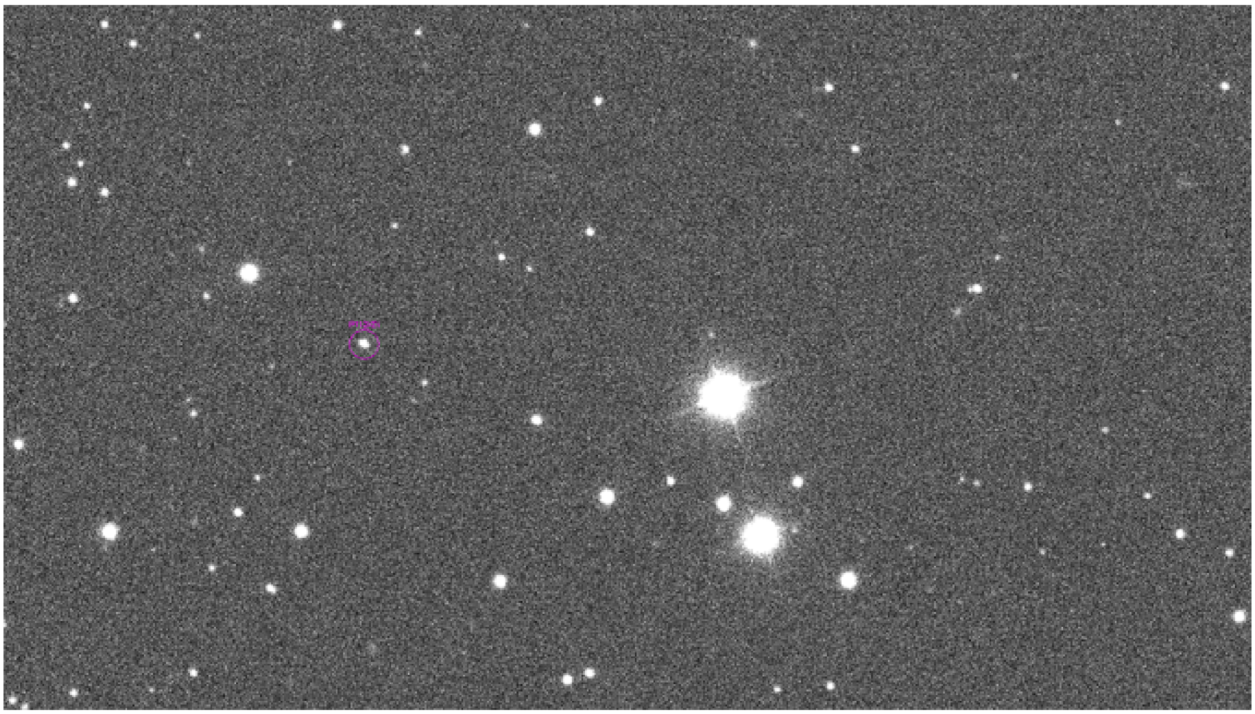


The asteroid belt and Trojan asteroids shown relative to the orbits of the inner solar system planets and the orbit of Jupiter.

Of particular interest for Earth is groups that are classified as near-Earth objects (NEOs) or potentially hazardous objects (PHOs). These objects are interesting not only from a scientific standpoint, but also because they could pose an existential threat to life on Earth. Famously, the extinction of all non-avian dinosaurs 66 million years ago was caused in large part by the impact of a large Earth-crossing asteroid. NEOs are defined as any object with a closest approach to the Sun of 1.3 au (one astronomical unit, abbreviated au, is the average distance between Earth and the Sun). PHOs are then objects that get even closer and are large enough to be dangerous, within 0.05 au of Earth's orbit at any point and larger than

~500 feet to be specific. In 2022, there were 2,304 PHOs known, which is estimated to be roughly 30% of the total PHOs that probably exist.

In order to find PHOs and determine if they have a chance of hitting Earth, we need to track them with telescopes. While stars remain effectively stationary over time in telescope images, NEOs can travel very quickly through an image. Because of the parallax effect, the closer an object is to Earth, the faster it will typically travel across the sky. This means that NEOs can be rapidly identified as fast moving objects in telescope images. Sometimes they can move so fast that they can move out of an image in a few minutes and if they are not followed, they may never be found again (or at least not for a very long time)!



An example of a minor planet moving through an otherwise stationary image of a star field.

As soon as an NEO is discovered, it is paramount to calculate its orbit quickly so that its future motion can be predicted and more observations performed to refine the orbit to a sufficient precision to ensure it is not a danger to Earth.

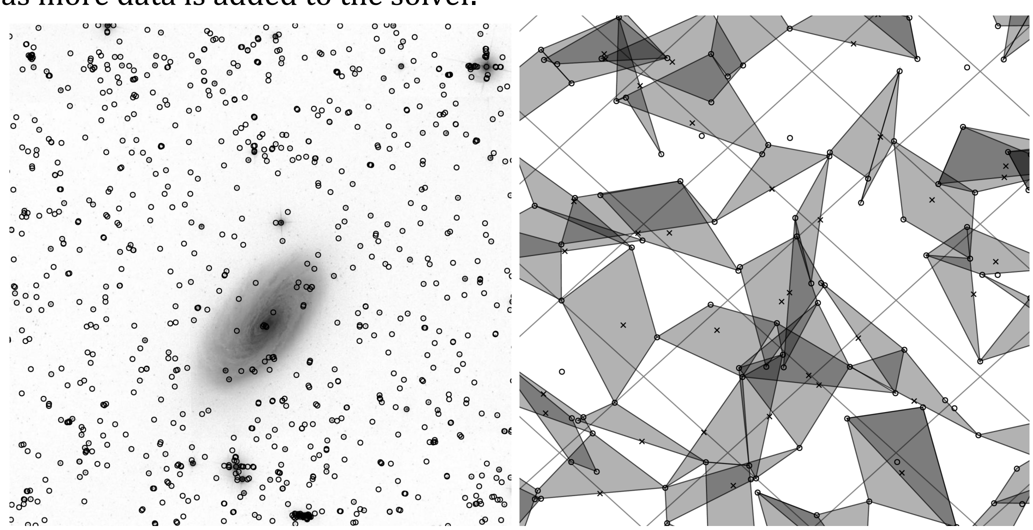
Calculating the orbit of an asteroid begins with astrometry. Astrometry is the technical term for the precise measurement of the position of an object over time in RA and Dec. An observation of a NEO will consist of multiple images of the object as it moves across the sky over minutes, days, months, and even years. By measuring the astrometry over time, we can gradually constrain the orbit based on the object's apparent motion. The details of how orbit determination is done requires complex vector mathematics, so it will not be addressed in this project (if you are interested in reading about one method on your own time, start here - https://en.wikipedia.org/wiki/Gauss%27s_method).

The premise behind astrometry is simple enough (measuring an object's position), but achieving high precision is where it can become challenging. Telescopes are accurate at pointing to specific locations in the sky to within a few arcseconds, but that precision is actually not high enough for precise orbit determination. Furthermore, an image is an area of the sky, not just one point. We need to somehow be able to convert the individual pixels within our image to coordinates in RA and Dec at levels more precise than one arcsecond.

The software we will be using for astrometry in this project is an open source tool called astrometry.net (https://astrometry.net/). Again, the details of how the software works is more complicated than can be covered in this project and astrometry.net is in itself a software engineering marvel, but we will cover the major ideas. Astrometry.net produces an astrometric solution for a given image by matching stars in the image to known star patterns located all across the sky. Essentially, astrometry.net has established a dictionary of millions of patterns between stars, and every pattern is unique to one set of stars in the sky and never repeated. When we give astrometry.net a list of stars in our image with their pixel locations, it scans through its massive dictionary of star patterns to find the exact set of stars we are looking at, then uses their locations in our image to produce a RA and Dec solution for every pixel in our image. Magic!

With the astrometric solution from astrometry.net, all we need to do is calculate the pixel position of our asteroid for each image, convert those values to a RA and Dec with the solution, and we are ready to solve for an orbit! **In this project, you will perform all of these steps to get an orbital solution from your own astrometric measurements.**

The more astrometric measurements we take, and the longer they are spaced out, the more precise our orbital solution will become. Data from one night can solve the orbit for long enough to find the object again a few nights later, but generally the orbit will not become very precise until the object has been observed for a large portion of its orbit - potentially weeks or months. At the end of this project, you will explore how orbital solutions get more precise as more data is added to the solver.



The left image shows the locations of lots of known stars as black circles around an image of a galaxy. The right image shows the unique patterns astrometry.net creates to uniquely identify the starfield.

Questions to Answer:

- What is the difference between an asteroid and a comet? What is a minor planet?
- What is the definition of a near-Earth object (NEO) and potentially hazardous object (PHO)?
- How are minor planets classified into different groups? What are a few large groups?
- How can a minor planet be detected in an image compared to a star?
- What is astrometry?
- How can we obtain precise astrometry for a given astronomical image?
- How can we determine the orbit of an asteroid from images?
- What factors influence the precision and accuracy of calculated orbits for a minor planet?

Data for your project

This project will use observations of the asteroid 2013 GG69 on the night of June 19th, 2022. The observations consist of ~10 images taken early in the night, then another 3 images taken a few hours later. You will determine if 2013 GG69 is an Earth-crossing asteroid and how often it completes one orbit. To begin, **open and follow the instructions in the .ipynb notebook**.

Goals for Project:

- Measure astrometry for an asteroid from one night of observations
- Format the astrometry for input to an orbital solver
- Explore how the orbital solution changes if astrometric data from other nights is added
- Determine if an asteroid is a PHO and how often it may approach Earth