

The Asteroids



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Abstract

In this tutorial you will learn about asteroids, a very interesting and current topic in our exploration of the Solar System and of planetary formation. You will learn about their orbital characteristics by querying a database.

Intermediate computer skills are recommended, as the tutorial requires the (guided) query of online electronic databases and use of histograms.

1 Asteroids in the Solar System

Planets aren't the only things orbiting our sun. Besides the planets there are many asteroids - leftovers from the time of planetary formation.

Our sun was initially surrounded by a large disk of dust and gas. Over time the particles in this disk collided with each other and began to form progressively larger objects, eventually creating the planets we know today. However, not all the material was used to form planets.

No large planets formed in the outermost regions of the Solar System, and Jupiter halted further planet formation in the inner Solar System with its enormous gravitational influence.

In 1801, the astronomer Giuseppe Piazzi observed a moving star-like object. At first, it was thought a new planet between Mars and Jupiter has been found, though as more and more objects were found in that general region of space, it became evident astronomers were dealing with a different class of body, later designated as “planetoids” or “asteroids”.

Today, we have discovered hundreds of thousands of asteroids between the orbits of Mars and Jupiter, forming the so called “Main (Asteroid) Belt”.

The main belt, however, is not the only place asteroids can be found. In 1992, an asteroid with an orbit outside that of Neptune was discovered. It was the first object of the “Kuiper Belt”, a much larger collection of asteroids than even the main belt.

Following the dynamic interactions between planets and asteroids, several asteroids were scattered away from their respective “belts”. As a result, asteroids can be discovered just about anywhere in the Solar system.

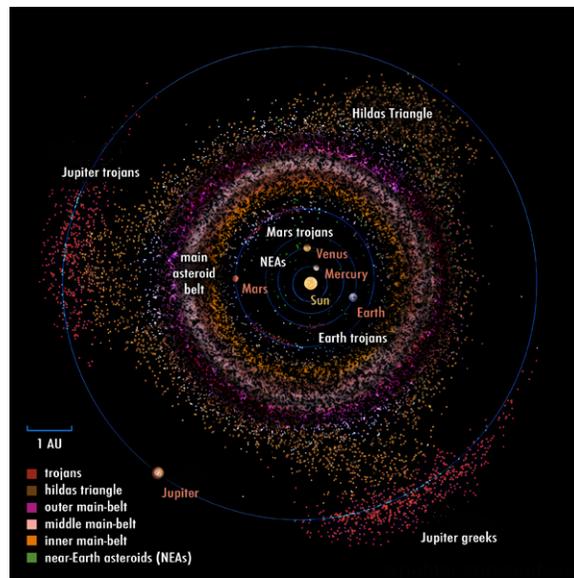


Figure 1: Graphic A top view of asteroid group location in the inner Solar system by Pablo Carlos Budassi / CC-BY-SA-4.0

All data concerning asteroids are administrated by the Minor Planet Center¹ (MPC) of the International Astronomical Union (IAU). They archive and analyze all observations of asteroids, using the data to calculate their orbits and publish them for the scientific community. The IAU also decides how the asteroids are named.

The large MPC database can be accessed via the Virtual Observatory, which makes it possible to learn about the basic properties of asteroids.

2 The MPC Database

The complete MPC database can be queried with different techniques in the data centre of the German Virtual Observatory (GAVO). The web form <http://dc.zah.uni-heidelberg.de/mpc/q/pla/form> at can be used to search the database with the most commonly used parameters. These include the orbital elements, the values describing the position and shape of the asteroids orbit.

Let us have a look at what orbital elements the MPC planetoid database uses.

The **semimajor axis** is defined as half the longest diameter of an elliptical orbit. In other words, it represents an estimate of the “size” of the orbit; see Figure 2 for an illustration. The unit used to measure the semimajor axis is the Astronomical Unit AU, which used to be defined as semimajor axis of the Earth’s Orbit. While in 2012 the astronomers decided to give it a fixed value², it is still right to think of “approximate radius of the Earth orbit” when reading AU.

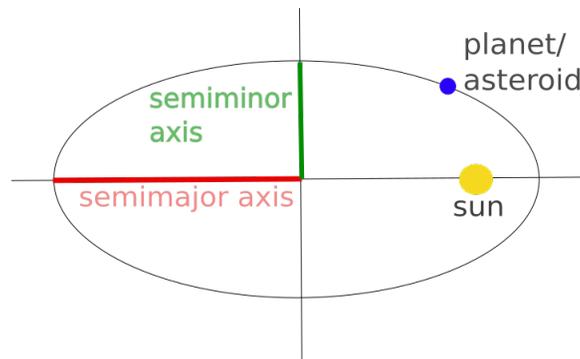


Figure 2: semimajor axis

¹<https://www.minorplanetcenter.net/iau/mpc.html>

²The Earth’s orbit slightly “wobbles” over time, and so does its major axis, so before 2012 the AU could change, which is not a good thing for a unit.

The measured **eccentricity** e of the orbit is defined as the deviation from a perfect circle, and has a value between 0 and 1, where 0 describes a perfect circle. An orbit with a value greater than 1 means the asteroid is leaving the Solar System, which is why you will not find anything like that in the database.

The semimajor axis and eccentricity give information about size and shape of the orbit. However, we do not yet know about the location and orientation of the orbit. To define these, three angles are needed.

The first angle is the **inclination** i . It describes the relative inclination of an orbits plane relative to the ecliptic plane. The ecliptic is the reference plane we use in our Solar System and it corresponds to the average orbital plane of the Earth. This is sketched in Figure 3.

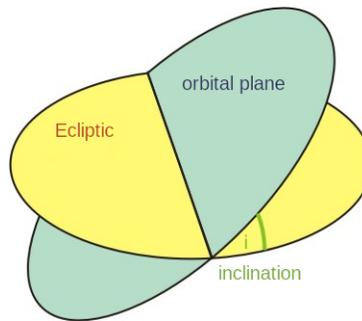


Figure 3: Inclination

The **longitude of the ascending node** Ω is the second angle (see Figure 4). The point where the orbit passes the plane of the Earth’s orbit (the ecliptic) from north to south is called the descending node, where it crosses from south to north is called the ascending node. The value of the longitude of the ascending node is the angle between the lines connecting the sun with the vernal point and the ascending node. This vernal point technically is where the celestial equator and the ecliptic intersect; in practical terms, it is what astronomers agreed upon as the equivalent of Greenwich on the sky, the point from where to count longitudes.

The **argument of perihelion** ω is the third angle (see Figure 5). It is defined as the angle between the lines connecting the sun to the perihelion (i.e., the point on the orbit closest to the sun) and the ascending node.

With these three angles (i , Ω , ω) it is possible to uniquely define the position of an orbital ellipse in space. We now know what the orbit looks like, which is great, but we still don’t know where the asteroid actually is.

To determine this there are different methods. The most commonly used is the mean anomaly. The mean anomaly is defined with the help of the “mean object”. The mean object is a virtual object with the same orbital period as

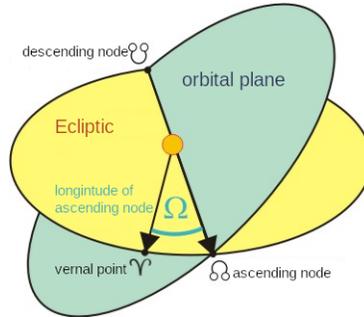


Figure 4: Longitude of ascending node

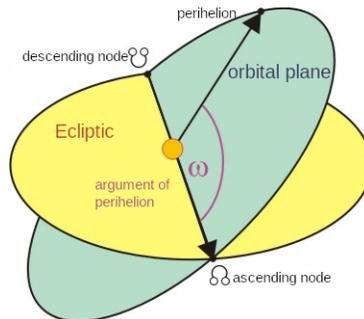


Figure 5: Argument of perihelion

the asteroid and which passes the perihelion at the same time. It is defined as having a circular orbit leading to a constant velocity for its entire orbit.

The lines connecting the centre of the circle to the current location of the “mean objects”, and the one connecting the centre of the circle to the perihelion is called the mean anomaly.

The MPC database can be searched using all of these values. Additionally, it is also possible to search the database for the epoch (the time when these values were first measured) and the absolute magnitude³ H of the object.

3 Investigating Asteroids in your Web Browser

As we said in the introduction, the asteroids are not distributed randomly. So, the first question we want to look at is: Where are all of the asteroids in our Solar System? The main belt between Mars and Jupiter is fairly well known,

³That’s the brightness the asteroid would have if it were at a distance of 1 AU from the sun and then viewed from there. Since most asteroids don’t come this close to the sun and

so let's first look away from the main belt (see a sketch of the Solar System in Figure 1). Mars' semimajor axis is 1.52 AU, and Jupiter's is 5.2 AU. So, let's look outside of Jupiter's orbit, far away from the main belt, with a semimajor axis between 6 and 7 AU.

- ▷ 1 *Load data from the database* – To do this, open the GAVO's MPC database in a Web Browser: <https://dc.g-vo.org/mpc/q/pla/form>. There, you can enter constraints to just select the objects you are interested in. Various fields such as *Name*, *semimajor axis*, or *eccentricity* can be constrained. The little links starting with “?” explain the syntax you can use for the constraints here; we want “value between x and y ”, which is written here with two dots. So:

1. In the field *Semimaj. ax.*, type 6 .. 7 (for “semimajor axis between 6 and 7 AU”).
2. Hit the button **Go** to run the search

Do not forget the space symbol before and after the two points. A table with all the known asteroids possessing a semimajor axis between 6 and 7 AU will load in your browser. At the time of writing this tutorial, there are 75 asteroids in this range.

By the way, at the bottom of the page you will also find a sort field, which allows you to sort the results, and a limit field giving the maximum number of records returned in case there are many matches. By default, that is 100, but it can be raised up to 250'000. However, if you let your browser handle that many result rows, things may get very slow and/or fail. We will later see ways to deal with result sets of that size (which you probably do not want to download in the first place). The queries below are chosen to keep the number of matches below 10'000, which on modern platforms should not overtax browsers.

- ▷ 2 *Understanding the properties of Asteroids around 6.5 AU* – It is hard to see much when staring at these 75 table rows. To gain insights into what you have retrieved, plot a histogram. To do that, you could download the results in, for instance, CSV (see “Output Format”) and use an external application – or you can use the **Quick Plot** option that the website provides.

After you click on **Quick Plot**, a graph will appear. Using the drop-down menus at the bottom of the graph, you can change the output to visualise what you want to see. For example, we want to see how the asteroids' inclinations, eccentricities, and semimajor axes are distributed. To do that,

1. Click on the button **Quick Plot**
 2. Select the left drop-down menu to be one of the properties (e.g., *Semimaj. ax.*)
-

3. Select the right drop-down menu to be **Histogram**

Interesting conclusions can be drawn from the histograms. Most of the asteroids between 6 and 7 AU have a rather non-circular (i.e., the eccentricity e is a good deal away from 0) orbits. In the distribution of the semimajor axes between 6 to 7 AU, you cannot see much structure; perhaps there is a bump around 6.25 AU, but then that could be noise, too. Looking at the histogram of inclinations reveals a reasonable concentration to the ecliptic ($i = 0$), but quite a few of these asteroids have orbits going far above and below the ecliptic plane (for reference: Mercury, the planet with the largest inclination, is at $i = 7^\circ$), some even orbit the sun against the rotation sense of the planet ($i > 90^\circ$).

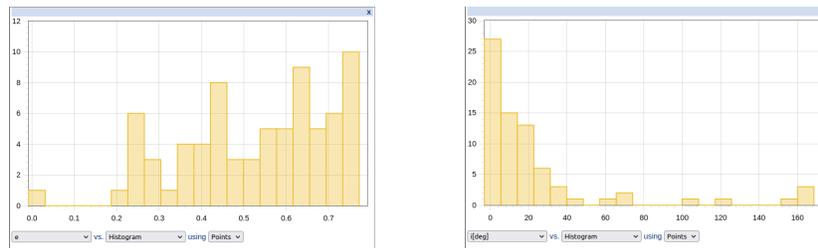


Figure 6: Histograms of the eccentricities (*left*) and inclinations (*right*) of asteroids with a semimajor axis between 6 and 7 AU.

- ▷ **3** *Comparing our findings with main belt asteroids* – To compare these asteroids with those of the main belt, we can look at the semimajor axis between 3.9 and 4.1 AU. The procedure is the same as described before except that you need to increase the limit up to 10'000 objects. If your browser really cannot handle this many entries, try with a lower limit – but be aware that this will skew your results uncontrollably.

Now, if you use the **Quick Plot** tool again and look at the different distributions, we can clearly see a difference to the asteroids within 6 to 7 AU. Most of the main belt asteroids have a more circular orbit, and in our small sample of them, there is a clear density peak around 3.97 AU. Looking at their orbit inclinations, it turns out that most of them are also much closer to the ecliptic than the objects farther out. Also note that there are way more asteroids (close to 6000 objects as we write this) found in a much smaller range of semimajor axes than for asteroids within 6 to 7 AU.

All these differences are mainly due to the overwhelming influence of Jupiter, which will expell objects on unruly orbits and clear orbits that would bring objects on them into resonances with Jupiter (i.e., very similar constellations every few revolutions, the effects of which will add up).

It would be nice to get a feel for how the asteroids are distributed in the whole Solar System. Thus, consider all asteroids within planetary orbits, say a semimajor axis smaller than 50 AU. For this, just type `< 50` in the search field *Semimaj. ax.*

If you run the same search as before, you will be warned that the results were truncated – you have exceeded the match limit. Not even the maximum limit of 250 000 would return all matches – and trying that would probably kill your browser.

We have reached a point at which one should not be downloading all the data for local analysis in the first place, and at which you want a more specialised tool than a web browser.

4 Server-side Analysis using TOPCAT, TAP, and ADQL

The software TOPCAT offers a much more flexible way to query data, in particular using a query language called ADQL (Astronomical Data Query Language). This lets you write little programs using a variation on the popular database query language SQL and have them execute on your behalf within the remote database.

TOPCAT is an interactive graphical viewer and editor for tabular data and it is frequently used in astronomy to manipulate astronomical data. It can be downloaded for free⁴.

- ▷ 1 *Finding the service holding the MPC and the MPC table* – With TOPCAT, you can access the asteroid data from the MPC with the following steps:

1. Open TOPCAT, go to the menu VO
2. Select **Table Access Protocol (TAP) Query** (a new window opens)
3. In the field *Keywords*, type `GAVO DC TAP`
4. Double click on it in the list (again a new window)
5. In the field *Find*, type `mpc.mpcorb` and select the service with clicking

With selecting `mpc.mpcorb` in the last step, we select the same database as we used in the first two steps of this tutorial.

- ▷ 2 *Running a first query* – Now, we are ready to type ADQL commands in the text box at the bottom to access the asteroid data we want to analyze. See the **Columns** pane for the columns of the `mpcorb` table; this is what you will get back, and this is what you can use in queries.

nobody can measure from there, this necessarily is a value derived from observations under different circumstances.

⁴<http://www.star.bris.ac.uk/~mbt/topcat/#install>

Let us begin with a small example to learn how to use ADQL to select and analyze asteroid data. At the bottom of the window select the button **Examples** → **Basic** → **Full table**. This fills the text box with a trivial example query,

```
SELECT TOP 1000 * FROM mpc.mpcorb
```

In this simple case, you can almost read the ADQL like English.

By clicking on the button **Run Query**, a new table pops up in the list of tables in TOPCAT's main window.

- ▷ **3** *Plotting a histogram in TOPCAT* – In the main window, click on the histogram icon to create a histogram plot. Select the option `semimaj_ax` to plot the distribution of the asteroids for their orbit sizes. While there is no guarantee exactly which 1000 records the database will choose with the construct above, it is quite certain that you will see that most of what you see will be between 1 and 5 AU.
- ▷ **4** *Increase number of analysed asteroids by aggregating server-side* – Since we are interested in the distribution of the semimajor axis of all the asteroids in this range, not only the some more or less random sample of 1000, we *could* download the whole catalogue and repeat the exercise – TOPCAT would actually let you do that. But it is much more efficient to create the histogram *on the server side* and then just download the histogram. This is possible using ADQL's `GROUP BY` construct. Consider:

```
SELECT ROUND(semimaj_ax*10)/10 AS bin, COUNT(*) AS n
FROM mpc.mpcorb
WHERE semimaj_ax BETWEEN 1 AND 5
GROUP BY bin
ORDER BY bin
```

There is a lot going on in these few lines – as said above, in ADQL you can write little programs. Some observations:

- We select the semimajor axis data of all asteroids in the MPC database with `SELECT semimaj_ax FROM mpc.mpcorb`
- With `... AS bin` we add a new, computed table column `bin` that we want to have the same value for all asteroids within a range of semimajor axes. In this example, we write `ROUND(parameter*10)/10`, which means that these ranges are one tenth of an AU wide (as in “from 4.45 to 4.55” – all of these are mapped to 4.5). Use a larger number than 10 to have smaller bins and hence higher resolution.
- The “aggregate function” `count(*)` computes the number of entries for each group. We let this end up in a computed column named `n`.

- where `semimaj_ax between 1 and 5` defines the interval to consider. Since the heavy lifting is done on the database side, we could as well look at the entire table, but by restricting our attention to the main belt, the result is a lot easier to plot.
- The phrase `GROUP BY bin` is what creates the histogram: it separates the whole result into subsets of identical `bin`, only returning one row per such group. Grasping this trick usually is the hardest part; having a close look at the result of the query perhaps helps a bit with this.
- `order by bin` finally makes it so the smallest bins come first. This just makes the result table a bit more readable.

Using the ADQL code above and hitting **Run Query** gives you a new table that you can now see in TOPCAT's main window.

- ▷ **5** *Plot the histogram table just retrieved* – Since we have retrieved already aggregated values this time (rather than the full table as before), you need some extra configuration in the Histogram plot. So, again hit the histogram button in TOPCAT's main window. The column `bin` should already be selected. This time, however, you also have to set **Weight** to the number of items in the bin, `n`. The histogram then shows the distribution of all asteroids between 1 and 5 AU. Make sure you also look at the table retrieved itself and appreciate that it is much smaller than what we retrieved in our first example – and yet it reflects the whole table rather than just a random subset of 1,000 asteroids.
- ▷ **6** *Plot the density across the whole solar system* – To push things further, we can also look at the asteroid distribution throughout the “whole” Solar System by constraining the semimajor axis from 0 to 50 (or perhaps dropping the whole `WHERE` clause). This will result in something like Figure 7.

To gain further insights, try different bin sizes (there is a slider for that in the **Bins** pane). Furthermore, there is a lot of dynamics in this plot (the ratio between the smallest and the largest value is large): The density between 1 and 5 AU is so large that the small densities are essentially invisible. In such a situation, it is usually a good idea to plot the *logarithm* of the value or, equivalently, have the logarithm on the axis. TOPCAT lets you do that: Go to the tab **Axes** and select **Y Log**. This will let you look at the high concentration in the main belt at the same time with the fine structure further in and out.

5 The different asteroid belts

- ▷ **7** *Main belt and resonances* – The histogram in Figure 7 gives us the general idea as to how the asteroids are distributed. The details however are hardly visible, because of the massive scale. To closer investigate the main belt between Mars

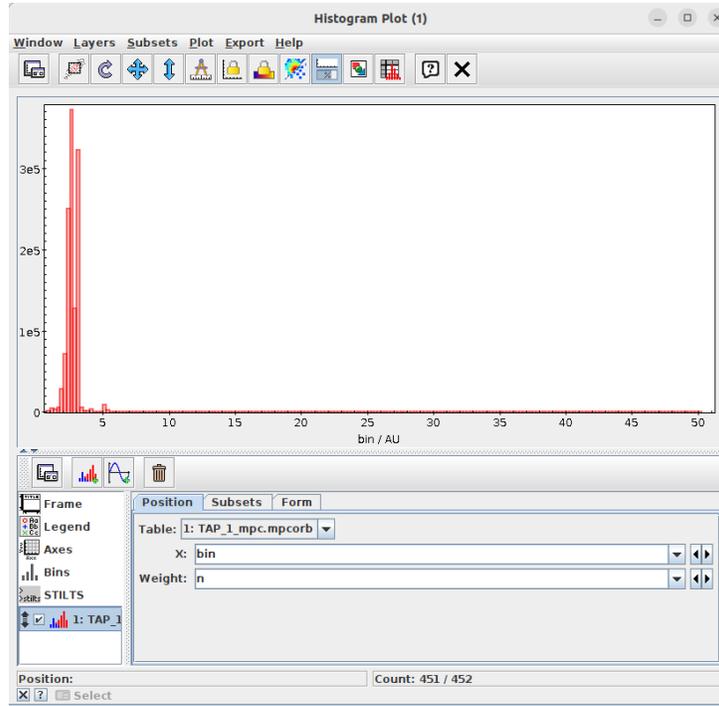


Figure 7: Histogram of the asteroid distribution in the Solar System

and Jupiter lets plot another histogram, this time limiting ourselves to asteroids with a semimajor axis between 0.5 and 6 AU.

The result should be along the lines of Figure 8. It is obvious that the asteroids are very unevenly distributed. Some groups of orbits are a lot more populated than others. For example, there are not many asteroids around 2.1 or 2.5 AU. Between 1.9 and 2.4 you will find a lot more.

These gaps in the belt are called Kikwood-Gaps. As mentioned above, these are caused by Jupiter and are in places where every few revolutions, the asteroid and Jupiter have the same relative positions. That way, moderate gravitational disturbances add up and kick the asteroid into a different orbit. In its place a gap is left.

The resonance can be calculated using Kepler's third law:

$$p^2 = a^3 \quad \text{or} \quad \frac{p^2}{a^3} = \text{const}, \quad (1)$$

where p is orbital period, and a is the semimajor axis. Due to this proportionality, we do not actually need to know the orbital period of the objects to

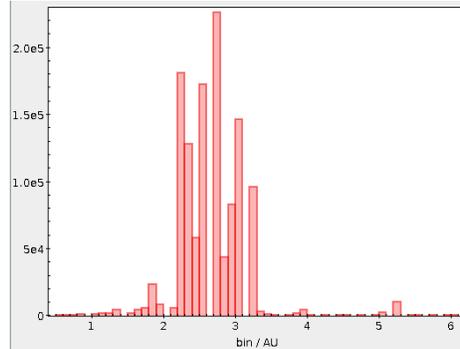


Figure 8: Main belt asteroid distribution

calculate the mean resonance.

However, given that getting the exact semimajor axis for these resonances is difficult with the histogram we have, it is easier to calculate the semimajor axis from the resonances; the criterion above translates that “every *few* years” (i.e., revolutions) the asteroid and Jupiter meet. In other words, their orbital periods are like $n : m$ for two small integers n and m , like, for instance, 4:1, 3:1, 5:2, 7:3 and 2:1.

Knowing this, we can take $p^2 = a^3$ and solve for p , yielding $p = \sqrt{a^3}$. To find where major semiaxes with resonance are, divide the orbital periods of the two bodies, with the larger orbital period going into the numerator. This yields $n/m = \sqrt{a_J^3/a_A^3}$. Given that we are looking for the semimajor axis of the asteroid, we solve for a_A^3 and arrive at

$$\sqrt[3]{(n/m)^2 \cdot a_J^3} = a_A.$$

When we calculate the semimajor axes for the resonances given above, we find 1.3, 1.73, 2.08, 2.23 and 2.6. Do you find these in your histogram?

In case you are curious: Are there resonances at the positions of the peaks (see Figure 8)? And can you figure out why there is a peak at the 1:1 resonance, exactly at Jupiter position?

6 The Kuiper belt

As previously mentioned, there is another asteroid belt at the outer edge of the Solar System. This belt is called the Kuiper belt, and is much larger than the main belt (20 times as wide and ~ 100 times as large) – though only a small fraction of its asteroids have been discovered to date.

The belt stretches from the orbit of Neptune at 30 AU all the way to 50 AU and most of the asteroids consist mainly of frozen compounds such as methane, ammonia and water. The most massive and probably the most famous object in the Kuiper belt is the dwarf planet Pluto (which for historical reasons is not in our database).

To take a closer look at the distribution of asteroids in the belt, let us plot another histogram, with a semimajor axis ranging from 37 to 50 AU.

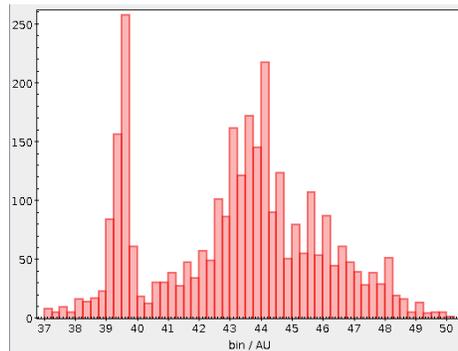


Figure 9: Kuiper belt asteroid distribution

Again we see a pattern of spikes and valleys, this time resulting from resonances with Neptune.

A clear peak can be found at 39.5 AU, a group containing Pluto, which is where this group got the name, “Plutinos”. Farther out, between 40 and 50 AU, is, if you will the main Kuiper belt.

Examine other the parameters you have encountered: eccentricities and inclinations. Start from our histogram-making ADQL code above and adapt the columns, ranges to be searched and bin sizes. For instance, the histogram of the inclinations should look like Figure 10.

Finally, try to recreate Figure 11, which shows the densities of asteroids in the Kuiper belt having inclinations of larger and smaller than 5 degrees.

One way to get this is by running two queries of the type

```
SELECT round(semimaj_ax*10)/10 AS bin, COUNT(*) AS n
FROM mpc.mpcorb
WHERE (semimaj_ax BETWEEN 25 AND 50) AND (inclination<5)
GROUP BY bin
```

Then do a second run with `inclination>5`; this will give you two tables, which you now need to combine into one plot. Open the histogram for the first dataset as usual, but this time, just below the histogram, click the second icon from the left (small histogram with a green “+”) to add another histogram

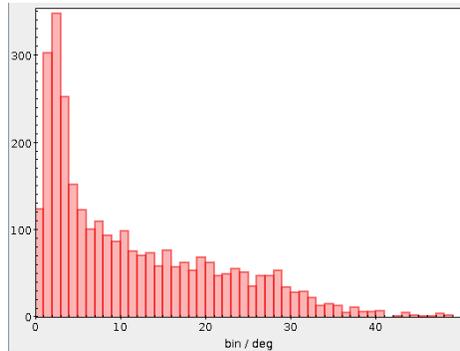
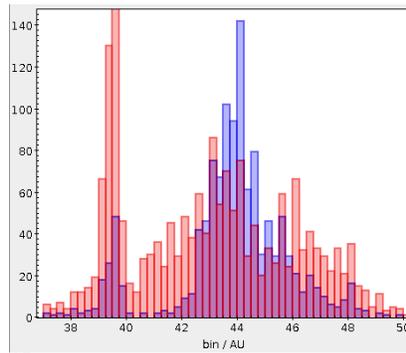


Figure 10: Inclinations of the asteroids in the Kuiper belt

Figure 11: Histogram of Kuiper asteroids over their semimajor axes with asteroids with an inclination < 5 in *blue* and > 5 degrees in *red*.

to your plot which pops up in the lower left corner with the description `<no table>`. By clicking that, you can select the additional data to be shown with the drop-down menu at **Table**. Select your second dataset and choose another color for it at the tab **Subsets**.

We observe that the “Plutinos” have a higher inclination than the asteroids in the classic Kuiper belt, which suggests that they are two distinct groups of objects that originated from rather different processes.

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