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Abstract

Pluto has been classified as a dwarf planet and with that became a member of the trans-Neptunian population defined as Plutinos that are in 2:3 Mean-Motion resonance (MMR) with Neptune. Despite its low mass it could still have a not negligible influence on objects in its vicinity that are even less massive and change their orbital elements in a way that they could evolve to Centaurs and Jupiter-family comets and to becoming potentially hazardous Near-Earth objects.

This study is aiming to understand the gravitational influence that Pluto has on trans-Neptunian objects and Centaurs, as well as on Plutinos in particular. It is to be investigated if Pluto significantly decreases the population size of the Plutinos and additionally what effect Pluto does have on the orbital evolution of minor bodies experiencing a close encounter with the dwarf planet.

Therefore, numerical integrations with the Lie-integration method were made for 50 Myr including Pluto into a simplified Solar System with the Sun and all planets. To determine the effects of Pluto the same calculations were made without including Pluto in the system.

It was found that Pluto has only a moderate effect on increasing the Plutinos leaving the 2:3 MMR of about 3%. In the integration with Pluto 31.1% of the Plutinos could be considered as fugitives, whereas 28.1% are found to be fugitives in a system without Pluto. Moreover, considering the orbital evolution of the Plutinos, 4 of 188 objects that performed at least one close encounter were found to leave the resonance in the system with Pluto and only 2 were found in a system without Pluto, which is consistent with Pluto having a moderate effect on the trajectories of theses bodies. As additional result this thesis found that 2 of 158 integrated Centaurs that performed a close encounter with Pluto entered the inner Solar System in a system with Pluto, which are 1.3%. However, in a system integrated without Pluto 5 Centaurs were found to enter the terrestrial planet region, which equals 3.2%. This could indicate that Pluto has a trending effect on sending Centaurs onto orbits towards the outer regions of the Solar System, which would be interesting to be investigated further.

Kurzfassung

Pluto wurde als Zwergplanet eingestuft und damit auch Mitglied der Transneptunische Population, genauer definiert als Plutinos in 2:3 Mean-Motion Resonance (MMR) mit Neptun. Trotz seiner geringen Masse könnte er dennoch einen nicht zu vernachlässigenden Einfluss auf noch weniger massereiche Objekte in seiner Nähe haben, und deren Bahnelemente so verändern, dass diese sich zu Centauren und Kometen der Jupiterfamilie und zu potenziell gefährlichen erdnahen Objekte entwickeln.

Diese Studie zielt darauf ab, den Gravitationseinfluss zu verstehen den Pluto auf Trans-Neptunische Objekte und Centauren sowie insbesondere Plutinos hat. Es soll untersucht werden ob Pluto die Populationsgröße der Plutinos signifikant verringert und zusätzlich welche Wirkung Pluto auf die orbitale Entwicklung von Kleinkörpern hat, die einen nahen Vorbeigang mit dem Zwergplanet haben. Zu diesem Zweck wurden für 50 Millionen Jahre numerische Integrationen mit der Methode der Lie-Integrationen durchgeführt, die Pluto in ein vereinfachtes Sonnensystem inkludiert mit der Sonne und den restlichen Planeten. Um die Auswirkungen von Pluto zu bestimmen, wurden die gleichen Berechnungen in einem System ohne die Einbeziehung von Pluto durchgeführt.

Es wurde festgestellt, dass Pluto nur einen mäßigen Einfluss auf die Erhöhung der Plutinos, die die 2:3 MMR verlassen, von etwa 3%, hat. Bei der Integration mit Pluto konnten $31,1\%$ der Plutinos als Ausreißer betrachtet werden, während $28,1\%$ Ausreißer in einem System ohne Pluto gefunden wurden. Darüber hinaus verlassen bei Betrachtung der Bahnentwicklung der Plutinos, 4 von 188 Objekten, die mindestens eine nahe Begegnung mit Pluto hatten, die Resonanz mit Neptun, während in einem System ohne Pluto nur 2 Plutinos die Resonanz verlassen. Das stimmt mit den Ergebnis überein, dass Pluto einen moderaten Einfluss auf die Bahnen dieser Körper hat.

Als zusätzliches Ergebnis fand diese Masterarbiet heraus, dass 2 von 158 integrierten Centauren, die eine nahe Begegnung mit Pluto durchführten in das innere Sonnensystem eintreten in einem System mit Pluto, das sind 1.3%. Allerdings wurden 5 Centauren gefunden, die in die Region der terrestrischen Planeten eintreten in einem System das ohne Pluto integriert wurde, das entspricht 3.2%. Dies könnte darauf hindeuten, dass Pluto einen Effekt auf Centauren hat der dazu führt, dass sich diese Objekte auf Umlaufbahnen entwickeln, die die äußeren Bereiche des Sonnensystems erreichen. Um das zu überprüfen werden weitere Berechnungen benötigt.

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1 Introduction

The search for an explanation of how the Earth and the Moon, the other planets, minor bodies and our Solar System as a whole evolved is a crucial topic since ancient times. It seems natural that mankind wants to know where it came from and therefore needs to find out how the Solar System and all its bodies emerged. Importantly the formation and dynamical history of minor bodies in the Solar System play a vital role in understanding its evolution as they imply that the bodies could not have formed at their current positions.

The minor bodies include comets, asteroids, trans-Neptunian objects or Kuiper-Belt objects, Oort cloud objects, small planetary satellites as well as interplanetary dust. It is known that some of these objects have not very much changed since their existence in the protoplanetary gas nebula and therefore contain unique information of how the Solar System evolved. The planets as well as the minor bodies, also known as planetesimals, were formed in the early Solar System, which is the result of researches in planetary theory. After the gas of the protoplanetary disk was exhausted the initial conditions for the dynamic history of the bodies that inhabit the Solar System were established. The planetesimal-driven migration model describes the dynamical migration of the giant planets and its influence on the minor bodies in the Solar System. It was precisely this migration of the giant planets that triggered the scattering of the small bodies, which led to the distribution that can be observed in the Solar System today (Nesvorný, 2018).

In 1930 Pluto was discovered with an eccentric orbit that crosses the orbit of Neptune and is located in a 2:3 Mean-Motion resonance (MMR) with Neptune. Along with one of its moons Charon, which was discovered in 1977, they have a mass of about $0.0022M_\oplus$ (Stern et al., 2018b). The identification of Pluto created belief in finding other objects located on orbits beyond Neptune. In 1951 G. Kuiper established a theory where no massive bodies could have formed beyond Neptune because of low density, which has left planetesimals moving around the Sun between 30 and 50 au (Kuiper, 1951). Only in 2006 Pluto was categorized as a dwarf planet and with that became an object of the trans-Neptunian population. Until the discovery of the first object orbiting beyond Neptune, *15,670 Albion* by Jewitt and Luu (1993), the trans-Neptunian region only existed in theory. Already some years earlier in 1977 the first Centaur *(2060) Chiron* was discovered by Kowal (1989). The objects in the trans-Neptunian region are mainly icy bodies and can be divided into four larger groups. (1) The resonant population that are characterized by a resonance with Neptune, for example the 2:3 MMR of Pluto and the Plutinos. The number of these objects is estimated to be 20% of the total population. (2) The Classical belt objects have non- resonant orbits between the regions of MMR with Neptune. This group of objects can be divided into 'hot' and 'cold' components and make up 70% of the trans-Neptunian objects. (3) The Scattered Disk includes objects with extreme orbits that could experience close encounters with Neptune. They are estimated to be about 10% of total TN-population. (4) Detached Scattered Disk objects are classified as bodies too far away for perceiving any planetary perturbation (Jewitt et al. (1998); Gladman et al. (2008); Fernández (2020) and sources within). This would also be the case with a possible 'Planet 9' (e.g. Batygin and Brown, 2016; Finch and Galiazzo, 2020).

The Plutinos located at the 2:3 MMR with Neptune are densely populated (Duncan et al., 1995; Melita and Brunini, 2000) and are among the sources of Centaurs (de Elía et al., 2008) and are even contributing to the population of the Jupiter-family comets (Muñoz-Gutiérrez et al., 2019). Plutinos show differences in their color distribution, those with low inclination have a redder surface compared to those with high inclination. This indicates that the Plutino population are objects that have been captured from cold-classical origin (Alexandersen et al., 2019). Interestingly, the Plutino population seems to have the highest fraction of contact binaries of 40% of the trans-Neptunian objects (Thirouin and Sheppard, 2018).

Centaurs are characterized as minor bodies with orbits between that of Jupiter and Neptune that have not been captured in any resonance with the giant planets. Moreover, their origin is in the Scattered Disk, on the one hand, and the Plutinos, on the other hand. A small contribution comes from the group of TNOs that are trapped in 2:1 MMR with Neptune, also called Twotinos. Furthermore, Centaurs can become part of the Jupiter-family comet (JFC) population or a Halley-Type object (HTO) after crossing the giant planet region, and with that they could also develop into Near-Earth objects. When entering the terrestrial planet region the physical and chemical characteristics of Centaurs are transformed, which raises questions about their collisional history (Peixinho et al., 2020). Centaurs play a vital role in understanding the evolution and the dynamics of the Solar System and therefore a lot of investigations were made regarding these objects. Since Centaurs can evolve to NEOs it is possible that close encounters and impacts with Centaurs had a part in the shaping of the Asteroid Main belt in the past (Galiazzo et al., 2016). Further investigation showed that 53% of Centaurs arrive in the terrestrial planet zone and 7% could have an interaction with terrestrial planets. They even could be responsible for delivering water on Earth with impacts. Because Jupiter and Saturn both are accountable for Centaurs becoming either Jupiter-family comets, or Saturn-family comets, Centaurs can also be interpreted as dynamically indistinct, which means that a Centaur could be responsible for the K-Pg-event (Galiazzo et al., 2019; Grazier et al., 2019).

The aim of this thesis is it to study the influence of Pluto in particular on the Plutinos as well as on trans-Neptunian objects and Centaurs, that cross the orbit of Pluto. It is to be investigated if Pluto significantly decreases the population of the Plutinos. Although Pluto has a very low mass compared to the other planets in the Solar System, it could still have a not negligible influence on objects in its vicinity that are less massive, leading to a change in their orbital elements. A close encounter with the dwarf planet makes it possible for minor bodies to reach areas influenced by stronger perturbations of the larger planets. Already in 1980 Fernandez (1980) stated that there exists the possibility that weak perturbations of minor bodies, such as Pluto, could deliver TNOs near Neptune's orbit, and with that further into the Solar System. To study the effect of Pluto on the orbital evolution of minor bodies experiencing a close encounter numerical simulations with the Lie-integration method (Hanslmeier and Dvorak, 1984) were performed of a sample of Plutinos, Centaurs and trans-Neptunian objects for 50 Myrs in a system including all planets as well as Pluto. To find out whether Pluto has any influence and how large it is, the same integration were made in a system that excluded Pluto.

Since Pluto itself is categorized as a dwarf planet but is also part of the trans-Neptunian population, the nature of Pluto could provide important implications for evolution of other small bodies in the Solar System (Howett et al., 2021). To improve the knowledge of the formation and evolution of our Solar System, theoretical models also need observations for confirmation and improvement. Especially explorations to the dynamically complex TN-region, and studies of its objects, are very promising to make an important contribution to the understanding of the formation and evolution of the Solar System. Therefore, new space missions, sky surveys and space telescopes are developed by different scientific institutions. For new and relevant insights in important Solar System issues, like formation and evolution of debris disks, solar nebular, and small bodies the New Horizon mission was designed, originally for the exploration of Pluto and its moons (Stern et al., 2018b). A fly-by of Pluto in 2015 brought back new data of the dwarf planet, which has been raising new questions. New Horizons's successor Persephone, the Pluto system orbiter and Kuiper-Belt explorer, is a NASA concept mission with its launch set to 2031 that wants to answer questions regarding Pluto and the diversity of the trans-Neptunian region (Howett et al., 2021). In addition, the James Webb Space Telescope (JWST) had its (long awaited) launch on the 25. December 2021[1] and it will be very promising for exploring the properties of the surfaces of TNOs and their compositions. Especially the near-infrared spectroscopy is capable of collecting compositional information of large and bright TNOs (Parker et al., 2015; Métayer et al., 2019; Norwood et al., 2016).

This thesis starts out with an overview of the Solar System and the objects it inhabits. It moves on to important dynamical theories regarding the Solar System and gives an introduction of the minor bodies considered in this thesis, the trans-Neptunian objects including the Plutinos, and the Centaur population. Chapter 3 describes the method used to perform numerical calculations with the Lie-integration method. In the same chapter also an overview of the Restricted Three Body Problem and a theory of close encounters will be given. Chapter 4 describes the results found in the numerical data, it contains a comparison for Plutinos that can be considered as fugitives in a system with and without Pluto. In addition this chapter gives examples of the orbital evolution of Plutinos, Centaurs, and TNOs that reach the inner Solar System. Chapter 5 points out different results of other studies that are compared to those found in this thesis. In addition, it adds how theoretical models can be improved with future results of observations made by the James Webb Space Telescope (JWST) or Persephone, a Pluto system orbiter and Kuiper-Belt explorer before Chapter 6 finishes the thesis with conclusions that can be made considering the important points of this work.

[1]https://www.jwst.nasa.gov/content/about/launch.html

2 Theoretical and Observational Characteristics of the Solar System

2.1 A Short Overview of the Solar System

The Solar System is a complex dynamical, physical and chemical system which consists of the Sun at its center, eight planets, at least five dwarf planets and a large number of small objects like satellites, asteroids, comets, rings, interplanetary dust and the solar wind. It is generally believed that the Sun and the bodies in the Solar System formed from a solar nebula of gas and dust. The age of the Solar System is estimated to be about 4.567×10^9 years.

The planets can be divided into two main groups according to their compositional structure and characteristics: (1) the terrestrial, or Earth-like planets, and (2) the giant or gas giant planets. Mercury, Venus, Earth and Mars are labelled as terrestrial planets due to their common silicate composition and iron core. Their structure can be explained by the process of chemical differentiation. During the formation of the terrestrial planets the gravitational potential energy heated the protoplanets which caused a melting process which separated material into different layers. The volatile component, including atmosphere, and oceans, was probably collected during the accretion process or delivered later via collisions with asteroids or comets. The nature of the terrestrial planets can be simply summarized as bodies with medium mass, with orbits near to the Sun, and with solid surfaces that show volcanism, and tectonic processes. All terrestrial planets have different atmospheres but did not accrete or could not hold onto nebula gas. Beyond that, the Earth is the only planet in the Solar System with the composition of atmospheric surface pressure, and temperature required for liquid water, which is required for life, as humans define it.

At larger distances from the Sun, in a region where ice could condense, and with more solid material available, the giant planets formed. Due to a larger material reservoir, the giant planets could form faster than the terrestrial planets, within only 10 Myrs. In contrast, the formation of the terrestrial planets took 100 Myrs of time. In general, the giant planets can be characterized with a low mean density, no solid surface, a possible silicate-iron core, and a massive hydrogen-helium atmosphere, which was presumably obtained from the solar nebula. This is also the reason for the compositional similarity between the giant planets and the Sun, only they contain more heavier elements. Uranus and Neptune's gaseous envelope is less massive than that of Jupiter and Saturn, which is a consequence of their later formation.

In 1801 the first dwarf planet was discovered, Ceres, at $\sim 2.77\,\mathrm{au}$, which later turned out to be the largest object in the Asteroid belt and the only dwarf planet in that region.

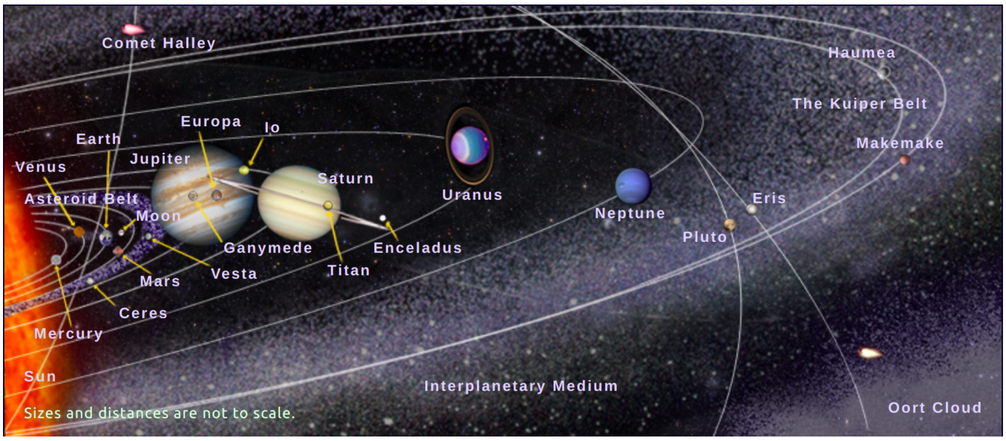

Figure 2.1: Illustration of the bodies in the Solar System[1].

Its compositional structure is comparable to carbonaceous chrondite meteorites, and it has a differentiated structure. Pluto was first identified in 1930 and is part of the trans-Neptunian population or Kuiper-Belt. It has five satellites, a thin and decreasing atmosphere and forms a planetary system with Charon. Moreover, only in 2004, at $35 - 51$ au Haumea was discovered, and in 2005 Makemake with $38 - 53$ au as well as Eris with $37.8 - 97.5$ au, which is part of the Scattered Disk. Furthermore, there still exists the idea of a Planet X or Planet 9 at very large distances in the Solar System. The solar nebula was hotter near the Sun and decreased with heliocentric distance, this temperature gradient is still imprinted in the bodies of the Solar System. In particular the Asteroid belt reflects this gradient, as the inner belt with distance $D \leq 2.6$ au contains more silicate rich objects, while the outer belt with $D > 3.3$ au contains volatile rich carbonaceous bodies. Besides the Main belt, also Near-Earth objects, Trojans, Centaurs and Kuiper-Belt objects or trans-Neptunian objects (TNO) are classified as asteroids according to their orbital elements and composition.

In addition, there exists a group of asteroids that are in resonance with Jupiter, for example the Hildas in 3:2 Mean-Motion resonance (MMR), and the Trojans in 1:1 MMR, which share the same orbit with Jupiter, but reside in the Lagrange Points L_4 and L_5 at $\pm 60°$ before and after Jupiter. Furthermore, Meteorites, which are bodies that find their way on the surface of Earth, are very important objects that contain a lot of information about the Solar System. For the same matter, also comets, which formed at very large distances from the Sun, and consist of very primitive material, are meaningful.

The Moon is an example of a satellite of a planet and probably formed due to a collision with proto-Earth and a protoplanet similar to Mars.

Furthermore, there exists a huge amount of dust in the Solar System, referred to as the Zodiacal dust cloud, which thickens near to the ecliptic plane. The dust grains are produced by comets as a result of their nucleus ice sublimation and from colliding

[1] https://contrib.pbslearningmedia.org/WGBH/buac18/buac18-int-toursolarsystem/index.html (screenshot)

asteroids.

Another component of the Solar System is the Solar Wind, an ionized plasma which is released from the Sun, and spreads through the whole system. It interacts with the bodies in the Solar System as it transports its magnetic field with it. At $\sim 84\,\text{au}$ a termination shock was discovered by Voyager 2, as well as the heliosphere and after that the heliopause, which forms the boundary of the Solar System (Weissman, 2007).

2.2 Relevant Dynamical Considerations

Isaac Newton's "Philosophiae Naturalis Principia Mathematica" or short "Principia", published in 1687, is one of the most important scientific works for modern science. Newton describes his three laws as well as the universal law of gravitation according to which all motion in the Solar System operates. Newton illustrates that the motion of two spherically symmetric bodies can be described by conic sections due to their mutual gravitational influence. In scalar form, where F describes the magnitude of force that operates between the two masses m_1 and m_2 that have a separation distance d the law's definition is

$$F = G\frac{m_1 m_2}{d^2} \tag{2.1}$$

with G representing the gravitational constant. Together with his three laws of motion Newton could describe the motion of objects that move around the Sun. Newton's laws are a good approximation for the description of the motion of bodies, however, Einstein's general theory of relativity is more precise.

In addition, he could prove that his laws can be derived from the three Kepler laws formulated by Johannes Kepler (1571 - 1630) in his book "Astronomia Nova" (1609) and "Harmonices mundi" (1619). The Kepler laws are an empirical description of the motion of the planets on orbits, but do not give a physical explanation. For the formulation of his empirical laws he used observations by Tycho Brahe (1546 - 1601). Because of that, it is important to note, that Kepler had no physical explanation regarding the motion of the planets as described by the three laws.

However, by adding more bodies into the system, the dynamical description becomes complex or chaotic. Chaos is determined by the initial conditions, which means that small changes in the starting conditions lead to a different result. With numerical integration it is possible to study the motion of bodies on very long timescales. Some results show that our planetary system could exhibit chaotic behavior, although currently the planetary orbits are stable. A lot of different studies emphasise that chaotic behavior has had a very important role in the formation and dynamical evolution of the Solar System as we observe it today (Murray and Lissauer, 2007).

2.2.1 Orbital Elements

The description of the orbital elements is an approximation for the motion of a body on an elliptical path about a massive central object due to its gravitational influence.

The perihelion distance q is defined as the closest distance between a body and the Sun, whereas the aphelion distance Q describes the furthest distance between the same objects, where $q = a(1-e)$ and $Q = a(1+e)$. For an elliptical orbit the major radius also called semi-major axis a is given by the mean of the perihelion and aphelion distances $a = \frac{q+Q}{2}$.

The deviation of a circular path is described with the eccentricity e, where $e = 0$ defines a circular orbit, $0 < e < 1$ an elliptical orbit, $e = 1$ a parabolic and $e > 1$ a hyperbolic trajectory. Considering the ecliptic plane, which is the plane of the Earth's orbit, as reference plane for our Solar System, a plane created by the orbit of an object can be inclined at a specific angle to the reference plane, which is labelled as inclination i.

Furthermore, the true anomaly v depicts the true angular location of an object relative to its perihelion position for a specific time or epoch. However, the mean anomaly $\mathcal{M}$ increases steadily over time by 2π radians every orbital period. At perihelion distance the value of the mean anomaly $\mathcal{M} = 0$, and for aphelion distance $\mathcal{M} = \pi$.

Ω is called the longitude of the ascending node, which is the angle between the reference direction and the direction of the ascending node, where the ascending node is defined as the position where the orbit crosses the reference plane. The argument of the perihelion or ω is the angle between the direction of the ascending node and the direction of the perihelion of the orbit.

With that the motion on a plane is defined, and with the given six orbital elements *(a, e, i, Ω, ω, v)* the position of an object can be described at any time for the three dimensional case. In general, the size of the orbit is defined by its semimajor axis a and the shape of it is determined by the eccentricity e. The position on a plane in relation to a reference plane is described by the inclination i, the argument of the perihelion ω and the longitude of the ascending node Ω. The value of the true anomaly carries the value of time as it defines the position along an orbit (Fitzpatrick, 2012; Moulton, 2010).

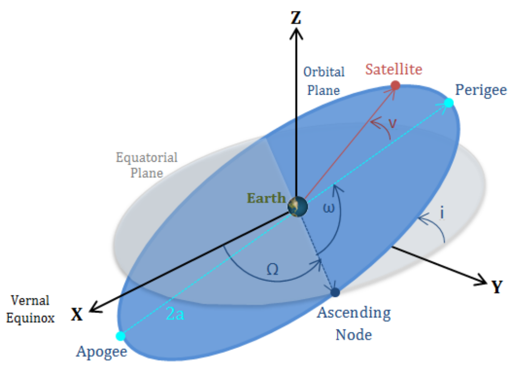

Figure 2.2: The six orbital elements a, e, i, Ω, ω, v [2].

2.2.2 Resonances

Resonances together with Newton's gravitational law play an important role in understanding the dynamics of the bodies in the Solar System. A resonance can be described as simple numerical relation between frequencies or rotational or orbital periods of bodies.

- Mean-Motion Resonance
  The Mean-Motion resonance (MMR) is the known term for orbit-orbit coupling, and describes the ratio of the mean motion or orbital frequencies n_1 and n_2 of two bodies when it is close to small integers, $n_1/n_2 = p/(p+q)$, where p and q are integers. There are a lot of examples for MMR in the Solar System, Jupiter and Saturn, which are near a 5:2 MMR, Uranus and Neptune near a 2:1 MMR, Saturn and Uranus near 3:1 MMR and Neptune and Pluto which are in 2:3 MMR and represent a class of objects in the trans-Neptunian region with the same resonance, known as the Plutinos. Furthermore, the Asteroid belt has a unique resonant structure which contain gaps in the radial distribution of the objects as well as accumulations. This structure is established under Kirkwood gaps, named after Daniel Kirkwood (1867) who first discovered these noticeable gaps in the belt that relate to resonances with Jupiter.

- Secular Resonance
  The Secular Resonance (SR) is defined as a long term resonance that is related to the precession of the orbits of the planets. In fact, in the SR the related frequencies include the rate of change of the proper longitude of pericenter or proper longitude of the ascending node of a body and the frequency of the perturbing body. A special form of the SR is the *Kozai*-resonance (Kozai (1962)) which is relevant for small objects with high inclination when $\dot{\omega} = 0$ where ω is the argument of the pericentre. It is possible that a body that gets disturbed by Jupiter would not get affected in its semi-major axis a, but could have changes in its eccentricity e and inclination i.

- Three-Body Resonance
  Beyond that, the Three-Body Resonance (3BR) includes a third body in the simple numerical relation as described before. This is the general description of the three body resonance
  $$k_1\dot{\lambda}_1 + k_2\dot{\lambda}_2 + k_3\dot{\lambda}_3 \approx 0$$
  with $\dot{\lambda}_1, \dot{\lambda}_2, \dot{\lambda}_3$ as the mean motion of the three bodies and k_1, k_2, k_3 represent nonzero integers. Especially the motion of asteroids in the main belt and in the Kuiper-Belt are important cases of the 3BR. For the case with three massive planets with masses m_1, m_2, m_3 it is valid that
  $$qn_1 - (p+q)n_2 + p_3 = 0$$

[2]https://www.gsc-europa.eu/system-service-status/orbital-and-technical-parameters

or

$$\frac{p}{n_1 - n_2} = \frac{q}{n_2 - n_3} = \frac{p+q}{n_1 - n_3} = \frac{P}{2\pi}$$

where $q = 1$ and $p = 2$, and P illustrates the period of time when they are aligned in a rotating frame. Considering this for the 3BR for Uranus(1), Neptune(2) and Pluto(3) which is a representative of the Plutinos it is valid that $n_1 = 2n_2 = 3n_3$ and $n_1 - 4n_2 + 3n_3 = 0$. With that the relation becomes $n_1 : n_2 : n_3 = 1 : \frac{1}{2} : \frac{1}{3}$. Another example is the Laplace Resonance among the three Galilean moons of Jupiter, where Io is in 2:1 MMR with Europa, which again is in 2:1 resonance with Ganymede (Murray and Dermott, 2000; Malhotra, 2013; Dvorak, 2013).

2.3 The Trans-Neptunian Region

Today trans-Neptunian objects (TNOs) are generally defined as icy bodies that orbit beyond Neptune and consist of a mixture of water-ice as well as other volatiles and minerals. About 100 years ago this region was generally unknown although Campbell, Aitken, and Leuschner already came up with theories of a possible planet and smaller objects in that region. In 1930 Pluto was discovered at Lowell Observatory in Flagstaff Arizona by Clyde Tombaugh with an unclear mass, and an orbit that crosses that of Neptune. What was particularly interesting about it was its high eccentricity and inclination compared to the other planets in the Solar System. In 1931 it was thought that Pluto could be as massive as 2/3 Earth's masses. In 1978 Charon was discovered by the US Naval Observatory in Arizona, as the largest of Pluto's five satellites, and with that Pluto became a double planet system. The remaining satellites were found in 2005 named Nix, and Hydra and in 2011/12 named Styx and Kerberos by the Hubble Space Telescope (HST). Due to the motion of Pluto and Charon around their center of mass the combined mass of the system is $\sim 0.0022\,\mathrm{M}_\oplus$ according to Stern et al. (2018a). In 2006 Pluto was declassified as a dwarf planet and with that became a member of the TN-region.

Already in 1951 Gerard P. Kuiper established a theory where in the region beyond Neptune between 38 and 50 au small bodies of about 1 km or larger could have formed, but not massive objects (Kuiper, 1951). This region is today known as Kuiper-Belt or Edgeworth-Kuiper belt because K. Edgeworth also claimed that the solar nebula must have reached regions beyond Neptune and thus inhabits small bodies (Edgeworth, 1949). Until the 1970s this region only existed in theory. In 1977 the first Centaur was discovered by Kowal (1989), today known as *2060 Chiron*. Already in 1980 J. Fernandez stated that there exists the possibility that an object the size of Pluto or the Moon could lead some TNOs near the orbit of Neptune. When this object is under the control of a giant planet it could be handed down to the next planet until found under the gravitational influence of Jupiter. With that dynamical development it is even possible that such an object could reach the inner Solar System. In the late 1980s an intense search for TNOs started but it needed until 1993 when the first one was discovered by Jewitt and Luu (1993) with the 2.2 m telescope of Mauna Kea, Hawaii. The first TNO is labelled as *15,670 Albion*, the second discovery followed only a few months later with *1993 FW*. Both objects have low eccentricity and a semi-major axis right where the TN-belt was expected to be, with $a = 43.82$ au and $a = 44.07$ au, respectively. Today the population of known TNOs is larger than 1000 objects and it is believed that there could exist more than 100,000 of these objects that are larger than 1 km (Morbidelli and Levison, 2007; Stern, 2007; Fernández, 2020).

2.3.1 Formation of the TN-Region

The formation history of the trans-Neptunian region has to explain the origin of the complex orbital structure that this region exhibits. In general three main classes are defined according to their dynamical properties, the cold and hot classical population, the resonant population, the Scattered Disk and the Detached Scattered Disk. The Nice model, originally published in 2005 (e.g. Gomes et al., 2005; Tsiganis et al., 2005) describes a phase of instability of the giant planets, after the removal of the gas of the protoplanetary disk phase, which had a significant effect on the dynamical evolution of the TN-region. This indicates that these minor bodies have survived until today in a region where they could not have formed. Recent models of accretion of planetesimals argue that planetesimals have formed from dust aggregates due to a mechanism called streaming instability (e.g. Simon et al., 2016). This mechanism produces an area of over-density of particles and therefore they drift to the star with less speed. As a consequence, the particles form clumps that can become self-gravitating when they get dense enough, then they contract and build up a planetesimal.

The planetesimal-driven migration model describes an improvement of the original Nice model. Initially five giant planets surrounded by a massive disk of planetesimals get captured in mutual Mean-Motion resonance (MMR) during the gas-phase of the disk. When the gas vanishes the giant planets form a multi resonant chain, and one of the giant ice planets gets ejected by Jupiter (Nesvorný and Morbidelli, 2012; Batygin et al., 2012). Furthermore, there exists a limit at ~ 30 au of the primordial planetesimal disk, beyond that distance no objects are orbiting. During the phase of giant planet instability, planetesimals are transported to the trans-Neptunian region. These first objects scattered to larger distances by Neptune experience an increase in inclination. Eventually they are captured in Mean-Motion resonance, and secular effects of resonance reduce their eccentricity and increase their perihelion distance, which makes encounters with Neptune impossible. As a consequence of the continued migration of Neptune the MMR breaks up and the objects are captured in the TN-belt conserving their inclination. To recreate the currently observed hot population Neptune migrations needs to be characterized as slow over a long range, as well as grainy (Nesvorný, 2015; Nesvorný and Vokrouhlický, 2016). In case of the cold classical population recent studies suggest that they have formed in-situ at a $>$ 40 au, where the influence of Neptune could not cause large orbital variations. This theory is motivated by the distinct size and color distribution of the hot and cold classical population, which implies a different origin. The non-resonant population is a result of the grainy migration of Neptune that scatters large planetesimals and destabilizes them so they get trapped on stable but non-resonant orbits. The Scattered Disk population are bodies scattered in the early Solar System and are less influenced by the giant planet migration. Detached Scattered Disk objects have been moved to very large distances by encounters with Neptune.

However, a lot of mechanisms and processes have not been fully described yet, which implies that further investigations and observations of these populations are needed to make better formation models (Morbidelli and Nesvorný, 2020).

2.3.2 Dynamical Structure of Trans-Neptunian Region

The TN-region has a very complex dynamical structure that is shaped by secular and Mean-Motion resonances. According to Jewitt et al. (1998) the region beyond Neptune can be categorized into three dynamical classes. (1) The classical trans-Neptunian objects (TNOs) that have low eccentricity with $e < 0.25$ and a semi-major axis between 41 au and 46 au. These non-resonant objects make up for about 70% of the TN-population and can be divided into a cold population with an inclination $i < 5°$ and a hot population with $i > 5°$. (2) The resonant TNOs that are in Mean-Motion resonance with Neptune with a number of about 20% of the TN objects. An example of this type of objects are the Plutinos including Pluto, that are in 2:3 MMR ($\sim$ 39.4 au) with Neptune. (3) The Scattered Disk objects (SDOs) that are defined as objects with extreme orbits with perihelion distances between 30 au and 40 au, semi-major axes as large as $\sim$ 90 au, and eccentricities of e $\sim$ 0.6. About 10% of the TN-population are categorized as SDOs. Furthermore, there exist (4) detached SDOs with perihelion distances $q > 40$ au and therefore are too far away to experience any planetary perturbations (Gladman et al., 2008; Fernández, 2020).

Figure 2.3 shows the orbital distribution of 1142 minor bodies from the four surveys OSSOS[3], CFEPS[4], HiLat[5] and Alexandersen et al. (2016) in a/e and a/i - plots including the four dynamical classes described above as well as Jupiter-coupled objects and Centaurs. Evidently, there exists a concentration of objects at 2:3 MMR with Neptune referred to as Plutinos, as well as a concentration at 1:2 MMR, labelled as Twotinos. In addition, observations made by OSSOS found other locations of Mean-Motion resonances in the trans-Neptunian region, such as 3:4 MMR (36.4 au), 4:7 MMR (43.7 au), and 2:5 MMR (55.4 au) (Bannister et al., 2018).

2.3.3 Properties of Trans-Neptunian Objects

A substantial property of a minor body population is the size distribution which gives information about their collisional processes. The size distribution is not easy to obtain since it is very difficult to observe the sizes of minor bodies directly. Therefore it is usually derived from the observed apparent magnitude distribution or the luminosity functions. The cumulative luminosity function (CLF) displays the number of objects per deg^{-2} near the ecliptic as a function of the apparent magnitude ($\mathrm{m_R}$) with $\Sigma(m_R) = 10^{\alpha(m_R - m_0)}$, where $\mathrm{m_0}$ is the magnitude at which $\Sigma = 1\,\mathrm{KBO}\,\mathrm{deg}^{-2}$ (Trujillo et al. (2001)). In other

[3]Outer Solar System Origins Survey
[4]Canada-France Ecliptic Plane Survey
[5]High-Latitude Application and Testing of Earth System Models

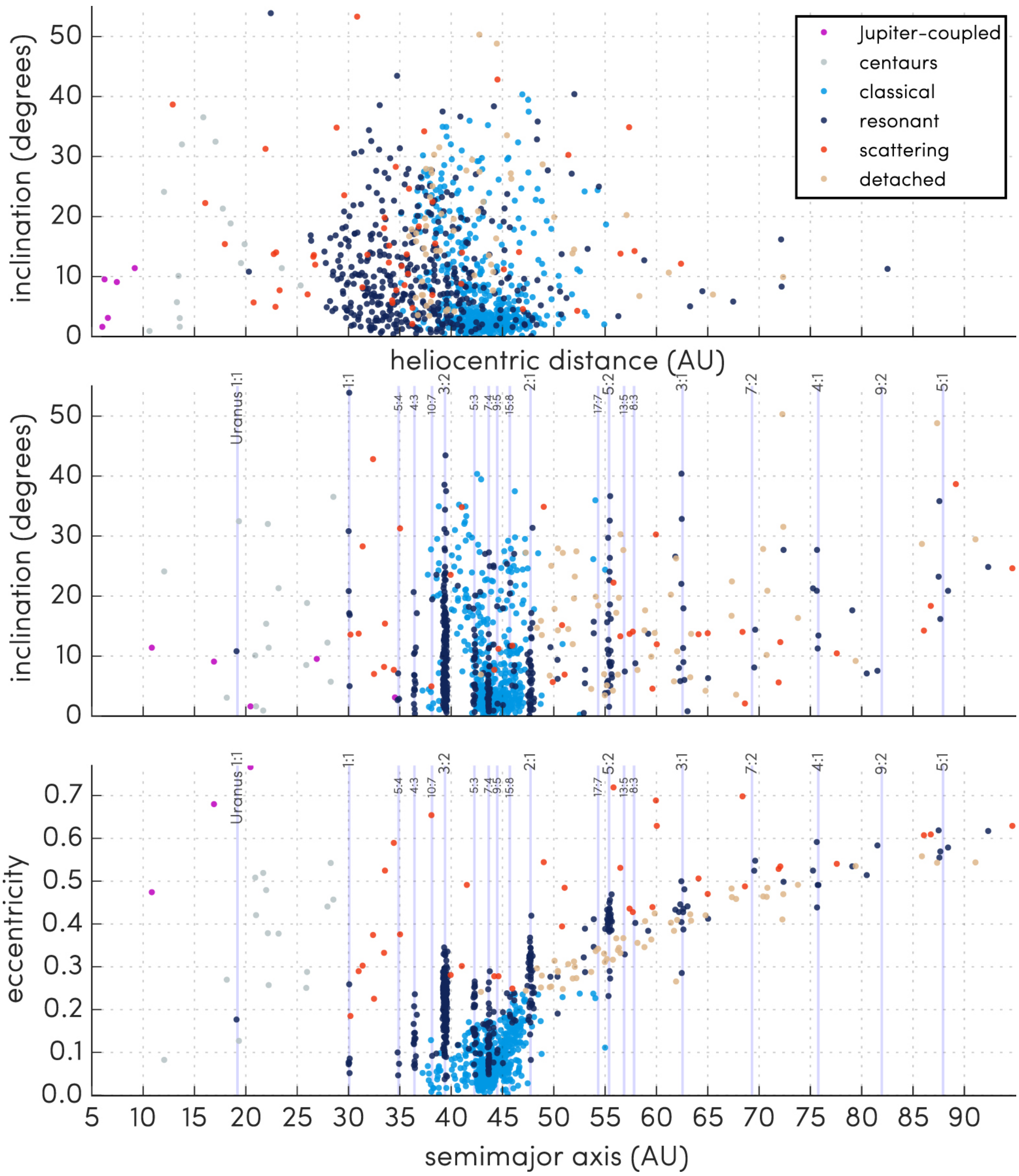

Figure 2.3: The orbital structure of the TN-region in a/i and a/e - plot with blue vertical lines depicting the semi-major axis location of Mean-Motion resonances found by the surveys mentioned above. The different dynamical classes are labelled according to a color scheme, Jupiter-coupled objects (violet), Centaurs (grey), classical TNOs (light blue), resonant TNOs (dark blue), Scattered Disk objects (orange), and detached SDOs (light brown) (Bannister et al., 2018).

words, the CLF reflects the number of minor bodies that are brighter than some magnitude m_R per square degree to the ecliptic. It is possible to convert the cumulative luminosity function (CLF) into a cumulative size distribution (CSD) with $q = 5\alpha + 1$ which is valid for a power law of the form

$$dn/dr \propto r^{-q}$$

For doing this conversion from luminosity to radius an average albedo for TNOs has to be chosen, which typically lies between 0.07 and 0.08 for TNOs and Centaurs, although they can be different for certain objects and correlate with color. The Kuiper-Belt depicts a steep luminosity function with $q = 4.5$ which could be an indicator of a short accretion period before the dynamical influence of the giant planets stopped it (Morbidelli and Nesvorný, 2020). However, the median albedo increases from Centaurs and Scattered disk objects with $\sim$ 5 - 6 %, to hot Classicals and Plutinos with $\sim$ 8 - 10%, and $\sim$ 14% for cold Classicals and $\geq$ 15% for detached objects (Müller et al., 2020). Furthermore, recent studies showed that for the hot and cold classical population as well as for SDOs the CLF is more accurate with a broken power law (Fraser et al., 2014).

According to Fraser et al. (2014) the absolute magnitude distribution or short H-distribution represented by a broken power varies for cold and hot population. These distinctions in the hot and cold population could be an indicator for a formation in different regions of the Solar System. The authors suggested that while the hot Classicals formed closer to the Sun, the cold Classicals formed 'in-situ' in colder regions. For the masses of the hot and cold population the authors found $\sim 0.01\,M_\oplus$ for the cold population and $3 \times 10^{-4}\,M_\oplus$ for the hot population.

The sizes of TNOs range from small objects (1 - 10 km), that are very difficult to observe, to very large objects that can be as large as Pluto (r $\sim$ 1200 km), for example Haumea with a diameter of D $\sim$ 1600 km or Makemake with D $\sim$ 1430 km. The largest objects in the TN-region all belong to the hot population. However, small objects are also important since it is possible that they become Jupiter-family comets (JFCs) and with that advance into the regions of the inner Solar System.

Trans-Neptunian objects are icy bodies found in the outer Solar System, that consist of water-ice, minerals and other volatiles, for example CH_4, N_2, CO and NH_3, which were observed in the Pluto-Charon system. Furthermore, they depict a wide range of colors which could be linked to physical properties, especially to the dynamical class of an object. This means that cold classical TNOs with $i < 5°$ show a red surface color, while the hot classical population with $i > 5°$, that include the Plutinos with high inclination and SDOs, reveal surface colors from neutral or grey to red. An explanation for this difference could be the sublimation of CH_4 when objects travel closer to the Sun, but there still does not exist a satisfying theory whether the different colors are the result of composition or evolution. In general, TNOs can be split in two large groups according to their color, on the one hand objects that show dark/neutral and red colors including Centaurs, SDOs, Plutinos as well as hot Classicals. And on the other hand cold Classicals, detached SD and outer resonant objects that only exhibit red objects.

For better understanding of the chemical and physical structure the bulk density of a TNO is substantial. A purely icy body has a density of about $1\,\mathrm{g/cm^3}$, whereas an object with a mixture of ice and rock reveals a density of $2 - 2.5\,\mathrm{g/cm^3}$. The bulk density can be derived from measurements of the size and mass of an object (Fernández, 2020).

2.3.4 Pluto and the Plutinos

Pluto is classified as a dwarf planet that describes an eccentric (e $\sim$ 0.25) and a high inclined ($i \sim 17°$) orbit, with a distance from the Sun that ranges from 29.6 au to 48.8 au and an orbital period of 248 years. Pluto is in 2:3 MMR with Neptune and crosses the orbit of Neptune due to the fact that its perihelion distance lies within the orbit of Neptune ($q_{Pluto} \cong 29.58\,\mathrm{au}, a_{Neptune} = 30.06\,\mathrm{au}$). In addition, it can be shown that the distance between Pluto and Neptune can never be smaller than 16 au (Milani et al., 1989). Pluto has a rotational period of p $\sim$ 6.387 days. With its largest satellite Charon, Pluto forms a double planet system, and it has four other satellites called Stys, Nix, Kerberos and Hydra, see Fig. 2.4. Charon has a radius of $606.0 \pm 0.5\,\mathrm{km}$, while Pluto's radius, which was observed during stellar occultations, is estimated to be $1188.3 \pm 0.8\,\mathrm{km}$, the uncertainty is due to the depth of its atmosphere. Together the system has a combined mass of $0.0022\,\mathrm{M_\oplus}$, where Charon exhibits about $0.12\,\mathrm{M_{Pluto}}$ (Stern et al., 2018b). Pluto's maximal, disk-integrated geometric albedo in the B-band ($\sim$ 4360 Angström) is $\sim$ 0.61, but due to its rotation this value varies between 0.44 to 0.61. The B-V color of Pluto itself lies at $\sim$ 0.85 mag. Pluto has a highly varying and distinct surface that shows extensive, bright and asymmetric polar regions, a large mid latitude and equatorial spots as well as km-large linear features. Its surface temperature ranges from 55 to 60 K. Pluto's bulk density lies at $2.03 \pm 0.06\,\mathrm{g/cm^3}$ which indicates that its mass is mainly composed of rocky material (60 - 80 %) and has formed a slowly escaping atmosphere (Stern, 2007).

Pluto belongs to the dynamical class of the trans-Neptunian region called the Plutinos with motion that is controlled by Neptune due to a 2:3 MMR ($a \cong 39.39\,\mathrm{au}$) with the giant planet. As Pluto's orbit crosses that of Neptune also some Plutinos are found to do the same for example *1993 SB* and *1994 TB*. Pluto is by far the largest member of its dynamical group. However, some estimations find that the amount of Plutinos larger than 100 km could be as high as 10,000 objects (Jewitt and Luu, 1996).

The 2:3 region in the TN-belt is densely populated, but as former studies have shown (e.g. Duncan et al., 1995; Melita and Brunini, 2000) there exist unstable orbits in the 2:3 MMR that could be responsible for objects to find their path to become Jupiter-family comets. Objects could escape stable orbits due to physical collisions or gravitational encounters or they could be bodies in a transitional phase. Furthermore, this proposes the possibility that these objects are collision fragments. In their study Alexandersen et al. (2016) investigated the orbital size distribution of Plutinos. They pointed out that their Plutino sample shows significant lower number of objects at $D < 100\,\mathrm{km}$ ($H_r = 8.7$, absolute r-band magnitude), which is also observed in the Neptunian Trojans. This proposes that the lack of large objects could be a trend in all hot TNO populations due to their collisional evolution. The analysis of their full data set are including Plutinos from the CFEPS survey as well as the 18 Plutinos they found with their deep survey. The authors prefer a moderately deep divot distribution at $H_t = 8.4$ to a moderalteyl steep slope, but could not exclude the knee distribution as described for hot TNOs by Fraser

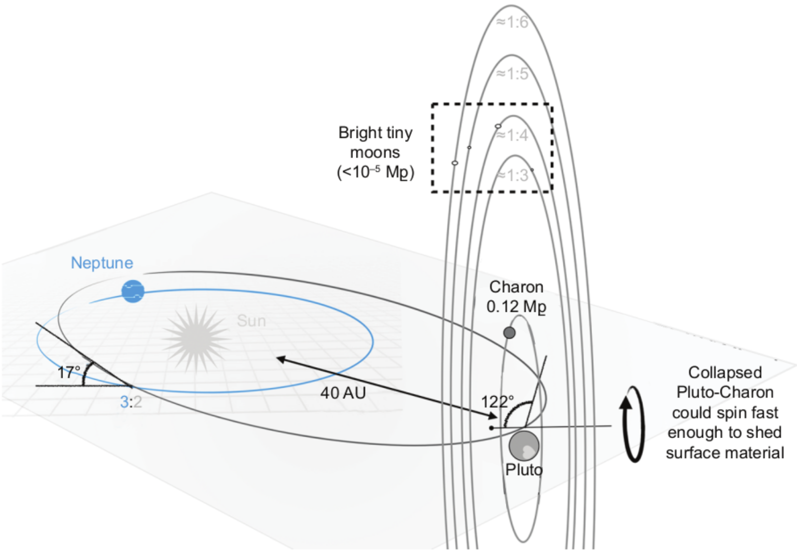

Figure 2.4: Pluto has a heliocentric orbit with an eccentricity of $e \sim 0.25$ and an inclination of $i \sim 17°$, it is in 2:3 MMR with Neptune. Its four small moons have orbits around the binary Pluto-Charon system, that are nearly in mutual MMR (Canup et al., 2020).

et al. (2014). Fig. 2.5 shows the cumulative distribution for the full Plutino data set of real and simulated detections from different models. The solution with the best match is a divot due to the fact that the survey detected no Plutinos with $8.27 < H_r < 9.01$ but found Plutinos with $H_r > 9.1$ (Alexandersen et al., 2016). Furthermore, they reported the existence of 9000 ± 3000 Plutinos with $H_r < 8.66$ as well as $37,000^{+12,0000}_{-10,000}$ Plutinos with $H_r < 10.0$.

Results of measuring the color distribution of Plutinos revealed that small ($H_r > 8.4$) bodies show different color distribution than larger ones ($5.5 < H_r < 8.4$), see Fig. 2.6. This indicates that the g-r color distribution depends on both, inclination and size of the objects. Objects of different size reveal a different forming mechanism, where smaller bodies can be mainly indentified as collisional fragments. Furthermore, Plutinos with low inclination ($i < 6°$) show a redder surface color compared to Plutinos with high inclination ($i > 6°$). These differences in color distribution according to inclination suggests that the Plutino population represents captured objects with cold classical origin (Alexandersen et al., 2019).

Five of the largest Plutinos are known to be binary or multiple systems, Pluto-Charon (plus four additional moons), Huya, Orcus-Vanth, Lempo and 2003 AZ84. Thirouin and Sheppard (2018) were studying data as well as literature and found that up to $\sim 40\,\%$ of Plutinos could be contact binaries, but less than 3% are currently confirmed.

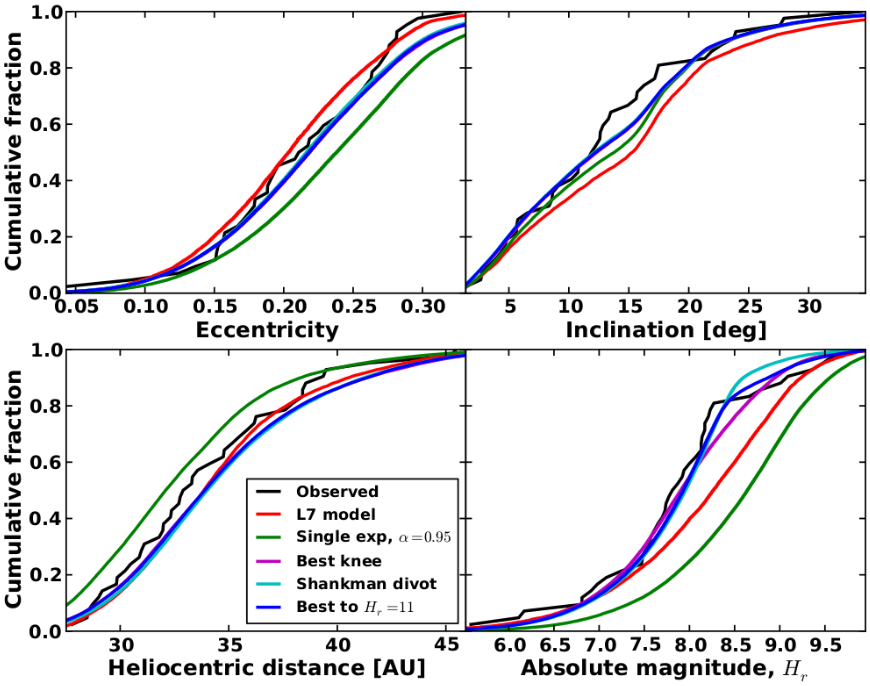

Figure 2.5: Cumulative distribution of full Plutino sample of real and simulated detections for different models. Simulations generated objects down to $H_R = 11$. The preferred solution is represented by the dark blue line with $H_t = 8.4, c = 6$ and $\alpha_f = 0.80$ (c is the contrast factor that represents the drop in number density, the exponent α_f gives the exponential function for faint objects), showing a moderately steep divot with a moderately steep slope, in addition the magenta line presents the best knee result (Alexandersen et al., 2016).

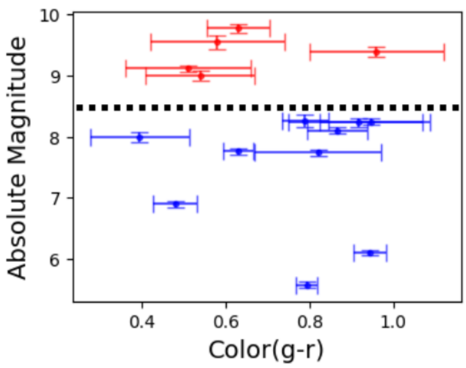

Figure 2.6: Distribution of absolute magnitude H_r against g-r color for a 15 Plutino sample. The dotted line represents the transition in size distribution for Plutinos (Alexandersen et al., 2019).

2.4 The Centaur Population

Centaurs are classified as minor bodies with orbits between that of Jupiter and Neptune but not captured in any 1:1 resonance with one of the giant planets. In a stricter classification Centaurs have a perihelion distance and a semi-major axis between the orbits of Jupiter and Neptune ($q > 5.2\,\text{au}$, $a < 30.1\,\text{au}$), see Fig. 2.7. The orbits of Centaurs are described as chaotic and short-lived (Peixinho et al., 2020). Unless otherwise noted, this section is adapted from Peixinho et al. (2020) and sources within.

Centaurs are also known to link the trans-Neptunian region with the Jupiter-family Comet (JFC) population. Their main source is the Scattered Disk on the one hand, and the Plutinos that are TNOs in 2:3 MMR with Neptune, on the other hand. Also the group of TNOs that are in 2:1 MMR with Neptune have a small contribution to the Centaur population. Centaurs can evolve to Jupiter-family comets when experiencing chaotic gravitational perturbations from the giant planets during their dynamical lifetime. The passage through the Centaur region is about 1 - 10 Myr and can lead to different outcomes. They either get ejected out of the Solar System by one of the Giant planets or back into the TN-region, Scattered Disk or even into the Oort Cloud. Others get under the gravitational influence of Jupiter, hence become a JFC and enter the inner Solar System (Sarid et al., 2019b). Jupiter-Family comets are dynamically controlled by Jupiter and have an orbital period smaller than 20 yr (Lowry et al., 2008).

2.4.1 Characteristics of Centaurs

Considering the UBVRJHK Johnson photometric system, Centaurs show surface colors that vary from neutral or grey with b-R= 1.0 mag to extraordinarily red with B-R= 2.0 mag. There still exists a limitation in observations because of telescope and instruments capacities only a minor part of known Centaurs can be investigated. Spectroscopically, Centaurs show the same characteristic properties as TNOs, like water-ice and methanol. Light curves of Centaurs show rotational periods and amplitudes, but a correlation between light curve amplitude and absolute magnitude which was notices among TNOs could not be observed in Centaurs, which is an indicator for a different evolution and collisional history. Stellar occultations are very helpful events to gain information about the shape, size, albedo of an object, but also to find out if it has rings, satellites or an atmosphere.

In general, Centaurs have a low albedo, the mean albedo of red Centaurs is $\sim 8\%$ to 12% while of grey Centaurs it is $\sim 5\%$ to 6%, but there also exist some exceptions with an albedo up to $\sim$20%.

A study by Müller et al. (2020) with 178 observed TNOs and Centaurs from Spitzer, WISE and Herschel data made investigations about their albedo, sizes and densities at thermal wavelengths (mid- and far-infrared, (sub)-millimeter). The authors found that in a sample of 55 Centaurs (Spitzer, Herschel, WISE) about 92% had a diameter smaller than 120 km which could mean that they are collisional fragments. The geometric albedos p_ν diverges from 3 - 4% for very dark to 50 - 90% for very bright objects. In Fig. 2.8 one can see the distribution of the albedo as a function of diameter for 170 objects in

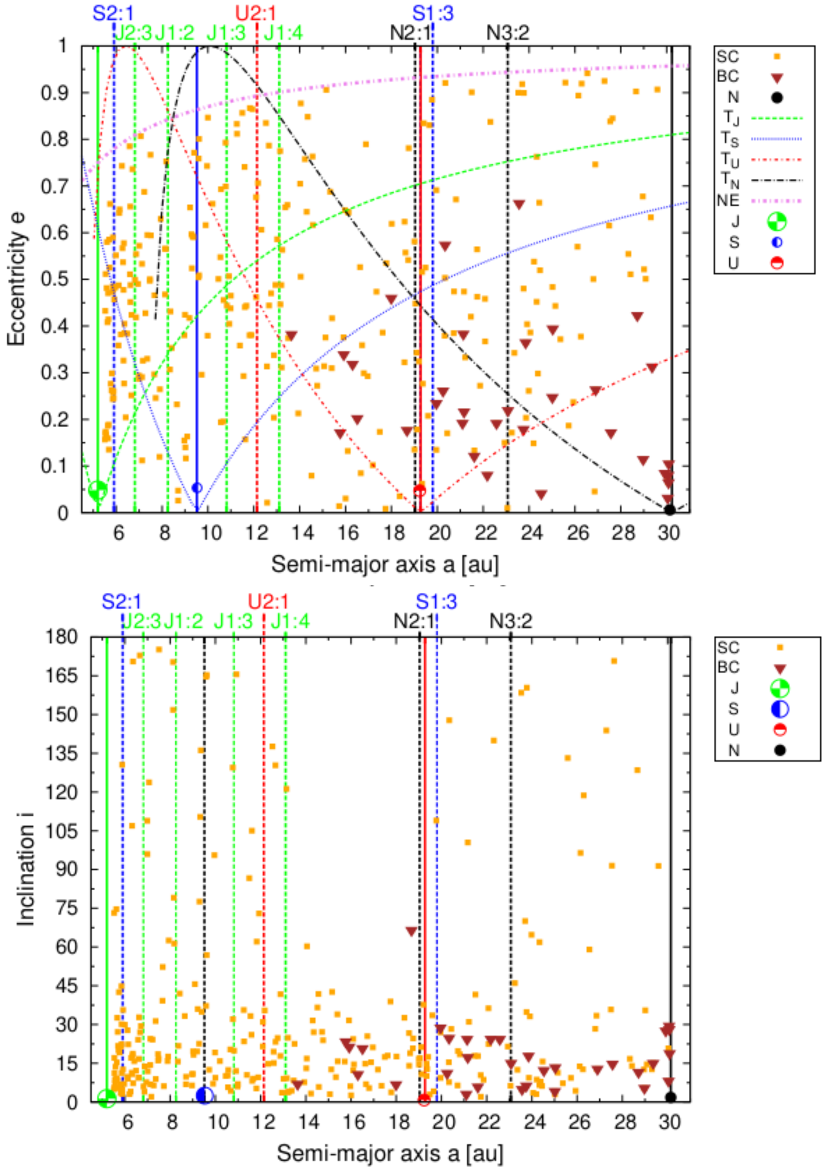

Figure 2.7: Orbital distribution of Centaurs between ∼ 5 - 30 au in a/e and a/i - plot. Labelled are small Centaurs (SC) with orange circles and large Centaurs (BC) for objects $D > 100$ km with red triangles. The vertical lines mark the position of MMR with the giant planets which are represented by circles. NE shows the border between Near-Earth objects and Centaurs, while the other lines represent the gravitational influence of the giant planets (Galiazzo et al., 2015).

the upper plot as well as the absolute visual magnitude vs. diameter in the bottom. According to this figure it is obvious that, except for very bright objects, there is no connection between albedo and diameter.

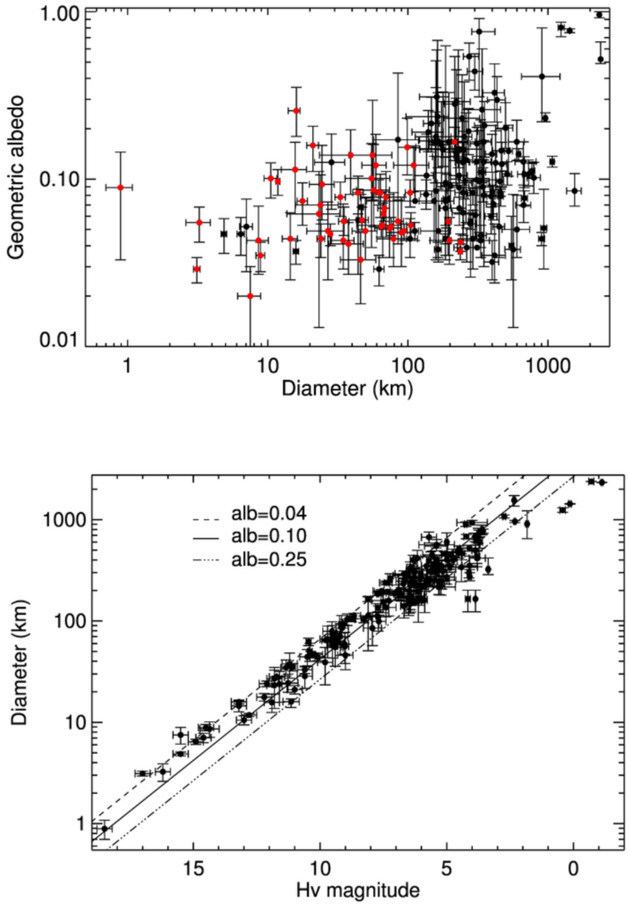

Figure 2.8: The upper plot shows the albedo vs. diameter for 170 TNOs (in black) and Centaurs (in red) from the data of Spitzer, Herschel and WISE. Obviously there exists a selection bias for small sized bodies. On the bottom the H_ν magnitude as a function of the diameter is illustrated. For a chosen albedo of about 10% the absolute magnitude gives a good size estimate (Müller et al., 2020)

However, as already mentioned, Centaurs and Scattered Disk objects have an albedo of $\sim 5-6\%$. Since the albedo of Centaurs and SDO are comparable it is reasonable that Centaurs origin in the Scattered Disk which also implies that they do not change their surface properties in the giant planet region. The Centaur population shows a distinctive color-albedo splitting where dark/neutral objects have a median albedo of $\sim 5\%$ and bright red bodies have a median albedo of $\sim 8.4\%$ as well as lower mean inclination

(Tegler et al., 2016). This is in agreement with an earlier study, which also found Centaurs are split into two classes according to their color, first with grey/neutral surface color with B-R < 1.4 mag and second objects with red surface color with B-R > 1.4 mag. In a sample of 49 objects with color and albedo information the authors found that grey objects have a mean albedo of $6\% \pm 2\%$ and red objects have a mean albedo of $12\% \pm 5\%$ (Bauer et al., 2013). Figure 2.9 depicts the bimodal color population of a sample of 148 objects of the TN-region and Centaurs.

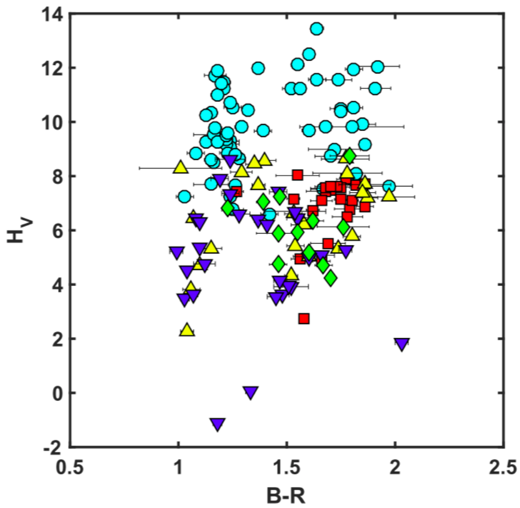

Figure 2.9: The plot depicts the absolute visual magnitude H_ν vs. the B-R color for Centaurs (cyan), hot Classicals (red), Plutinos (yellow), SDOs (dark blue) and non-Plutino resonant (green). Objects with $H_\nu > 7.0$ and $H_\nu < 6.0$ show a two color population despite their dynamical class (Tegler et al., 2016).

Also binary systems and rings can be observed among Centaurs. Until now two binary system are known between Ceto and Phorays and Tychon and Echidna. In 2013 *(10199) Chariklo* was the first Centaur where a ring system was observed by observing stellar occultations (Braga-Ribas et al., 2014), but formation and stability of such ring systems around these objects are still unclear (Sicardy et al., 2020). About 8% to 9% of the Centaur population show magnitude variations on small timescales which is an indicator for cometary activity (Peixinho et al., 2020).

2.5 Correlation between TNOs, Centaurs and Jupiter-Family Comets

It is undoubtedly that TNOs travel through the giant planet region and can become a Jupiter-family comet (JFC). Centaurs can be seen as a population in a transition state between trans-Neptunian objects and Jupiter-family comets. Centaurs are the progenitors of Jupiter Family comets (JFCs) which are under the gravitational influence of Jupiter and characterized with keeping a Tisserand Parameter between 2 and 3. Early studies have shown that the dynamical evolution of JFCs is influenced by long term gravitational perturbations of the giant planets that create weak orbital chaos (Volk and Malhotra, 2008).

Di Sisto and Rossignoli (2020) studied the contribution of the Scattered Disk to the Gaint Planet Crossing (GPC) population defined with 5.2 au $< q <$ 30 au and Centaurs (5.2 au $< a <$ 30 au) with numerical simulations. The simulations investigated the dynamical evolution of 5770 massless particles together with the four giant planets and Pluto over the time of 4.5 Gyr. The results showed that 0.3% of the particles collide with a planet, while 50.6% reach a semi-major axis of $a > 500\,\mathrm{au}$, 15.5% reach the zone with $r < 5.2\,\mathrm{au}$ and 33.8% remain as SDO. The simulations also showed that Pluto has a small effect on the contribution of GPC and Centaurs and therefore also contributes to the population of Jupiter-family comets. They found the rate of injection of SDOs to GPC with $5.2 \times 10^{-10}\,\mathrm{yr}^{-1}$ and a number of GPC with R $>$ 1 km to be 2.23×10^{8}. These results are different than those from Volk and Malhotra (2008) because they use a different debiased model in their simulations. Figure 2.10 shows the cumulative number of Centaurs vs. diameter from the different source reservoirs in the TN-belt.

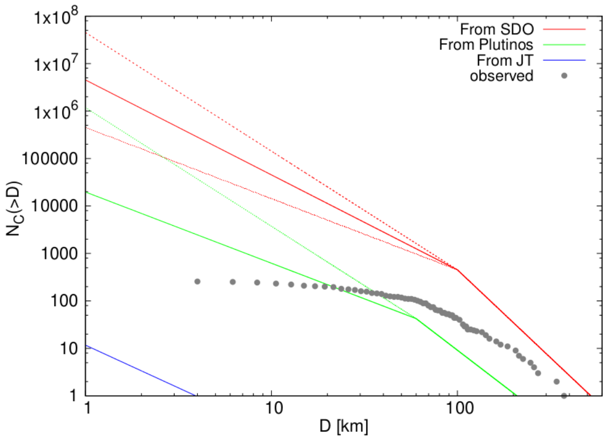

Figure 2.10: Cumulative number of Centaurs vs. diameter D from different source reservoirs like SDO in red, Plutinos in green and Jupiter Trojans in blue. The grey dots represent the observed Centaur population with an albedo of 6% (Di Sisto and Rossignoli, 2020).

The size distribution of JFC follows a power law with the index -2.7, where the majority of JFC are rather small and have sizes between 1 to 10 km. With these estimates a population of $\sim 0.8 \times 10^8 - 1.7 \times 10^8$ Scattered Disk objects larger than D $>$ 1 km are necessary to provide the observed JFC population from the source region between 30 and 50 au. The fractional escape rate of SDOs was estimated to be $1 \times 10^{-10} - 2 \times 10^{-10}\,\mathrm{yr}^{-}1$, which relates to 40 - 60% of the population size that existed about 4 Gyr ago. Furthermore, also cold classical TNOs, resonant TNOs and the Trojans of Jupiter constitute to the JFC population (Volk and Malhotra, 2008). Plutinos can also be influenced by perturbations of the giant planets and therefore represent another source for JFCs. The Plutinos are a population that, including Pluto, are in 2:3 MMR with Neptune and classified as resonant TNOs. The gravitational influence of Pluto may be responsible for some Plutinos to leave the resonance and cross the orbit of Neptune and with that could become JFCs during their dynamcial lifetime. Di Sisto et al. (2010) found that of a sample of 1179 Plutinos that escape the resonance 67% of the particles get ejected, 32.7% reach the zone interior to Jupiter and 0.3% collide with one of the giant planets. Plutinos that escape the resonance with Neptune find their way either into the Centaur zone or into the Scattered Disk. Their mean lifetime in the Centaur zone is $\sim$ 108 Myr, which is higher than the mean lifetime for Centaurs from the SD zone with $\sim$ 72 Myr. The difference in mean lifetime does not depend on the initial inclination of the source reservoir. Numerous encounters with the giant planets changes the inclination, which makes it impossible to determine whether a Centaur originated in the classical TN-region or in the SD (Volk and Malhotra, 2013). The number of Plutinos that contribute to Centaurs with D $>$ 1 km is estimated to be 1.8×10^6 - 1.8×10^7 objects, which means that they represent only a secondary source of Centaurs, which supply less than 6% in total to the Centaur population (Di Sisto et al., 2010).

Fernández et al. (2018) studied the difference between the dynamical evolution of inactive and active Centaurs in the Jupiter-Saturn region, where the onset of activity is believed to take place. According to the authors the Centaurs that travel to the inner planetary region either evolve to a JFC with a period of 20 yr or to a Halley-Type comet (HTC) with a orbital period between 20 and 200 yrs. Computations revealed that inactive Centaurs ($T_J < 2.5$) mainly evolve to HTCs while active Centaurs with $T_J > 2.5$ evolve to JFCs and only a few become HTCs. In addition, the dynamical timescale of inactive Centaurs is twice as long as that for active Centaurs. Since both types of objects have the same source reservoirs it is likely that not intrinsic physical properties are responsible for this transformation, but their different dynamical evolution.

The zone between Jupiter and Saturn is regarded as a transition zone where Centaurs could remain inactive as well as a region where effective dynamics occur and where the onset of activity of JFCs happens. Furthermore, this region is characterized as unstable which means that orbits can change fast (Di Sisto and Rossignoli, 2020). But since Jupiter and Saturn are close to a 5:2 MMR there exist regions in the Centaur region that are nearly in Three-Body resonance (3BR) with both giant planets, for example J2 : 3 : S1 (6.04 au), J2 : 5 : S5 (6.82 au), J3 : 7 : S3 (7.315 au) and J1 : 6 : S5 (8.261 au) (Roberts and Muñoz-Gutiérrez, 2021). A very prominent member of orbiting the region just outside Jupiter is 29P/Schwassmann-Wachmann 1 (SW1). SW1 is an active and large Centaur which was discovered in 1927 while outbursting, and was motivation for describing a region where Centaurs orbit, just before becoming JFCs (Sarid et al., 2019b; Roberts and Muñoz-Gutiérrez, 2021). In this region the temperature is mainly too low for water-ice to sublimate, which gives reason that this can not be the main source of material that drives the activity of comets. Therefore more volatile elements must be accountable for that, like for example CO or N_2 ices. Sarid et al. (2019a) defined a "Gateway region" where Centaurs orbit before becoming JFCs between 5 and 7 au, with four observed members including SW1. It is possible that JFCs experience an onset of activity in that region. In their studies the authors found that 77% of Centaurs in the Gateway region become JFCs and that 66 - 77% of all JFCs pass through that region. In a very similar way Roberts and Muñoz-Gutiérrez (2021) described a "Near-Centaur region" with $q > 5.204$ au and $5.6 < Q < 9.583$ au with 15 objects currently orbiting there. Fig. 2.11 shows a comparison between the two regions mentioned including the 15 objects currently observed there.

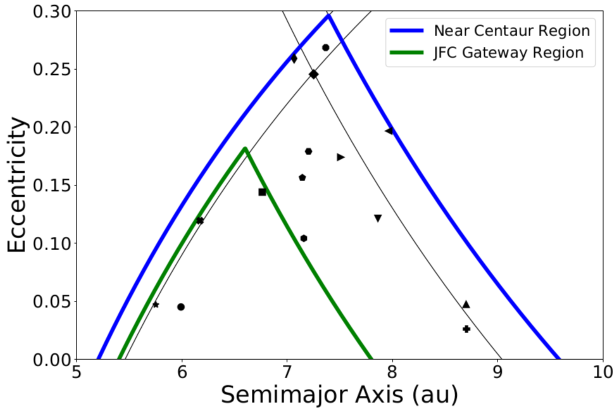

Figure 2.11: Comparison between the two regions of Centaurs becoming JFCs, with 15 objects currently orbiting there. The thin black lines correspond to the constant perihelion at the aphelion of Jupiter and the line of constant aphelion at the perihelion of Saturn (Roberts and Muñoz-Gutiérrez, 2021).

Jupiter is responsible for the transition of Centaurs to JFCs and with that increases the amount of objects in vicinity to Earth. Furthermore, also the influence of Saturn can deliver material to the Asteroid belt and into the terrestrial planet region, these objects are called Saturn-Family comets (SFCs) (Grazier et al., 2019).

Knowing this, it makes the theory of a large body like a Centaur evolving to a JFC and becoming the reason for mass extinction on Earth, plausible and possible. Investigations of bombardments in cratering records showed that is more likely that impacts occur rather episodically, consequently also TNOs and Centaurs can be seen as hazardous to Earth. A large cometary body that enters an Earth-crossing orbit could collapse into smaller debris which would increase the possibility of a bombardment. *95P/Chiron* was the first Centaur discovered, its chaotic dynamical behavior could be responsible for it to arrive on Earth-crossing orbits, see Fig. 2.12 (Napier et al., 2015; Napier, 2015).

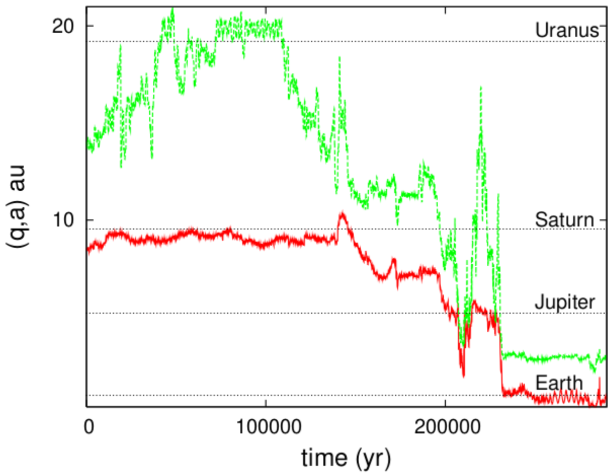

Figure 2.12: This figure shows a 95p/Chiron clone becoming a Earth-crossing object. The semi-major axis is represented in the green line, and the perihelion distance as a red line (Napier, 2015).

Investigations showed that Centaur clones could experience close encounters with all planets, although real impacts only happen with the giant planets and not with the terrestrial planets. Centaurs can therefore be seen as one of the main sources that produce Near-Earth objects. They potentially brought water into the inner planet region and could have caused disruptions among the asteroids in the Main belt about 3.5 Gyr ago (Galiazzo et al., 2016).

Galiazzo et al. (2019) identified a subregion that produces more encounters with terrestrial planets at 5.5 au $<$ a $<$ 8 au with 0.09 $<$ e $<$ 0.75. The inclination has an initial dominant region for $8° \leq$ i $\leq 40°$ which decreases to $i \sim 30°$ at $a \sim 24$ au. The prominent inclination of $i \sim 20°$ is similar to the value of Jupiter-family comets which are the progenitors of Centaurs. In their investigations the authors found that 53% of the Centaurs enter the terrestrial planet region and 43.4% of the Centaurs become Near-Earth objects during their dynamical lifetime. Of all Centaurs 82.4% escape the Solar System, 6.2% collide with the Sun and 0.9% experience impacts with planets. About 7 - 8% of all Centaurs could encounter the terrestrial planets, see Fig. 2.13.

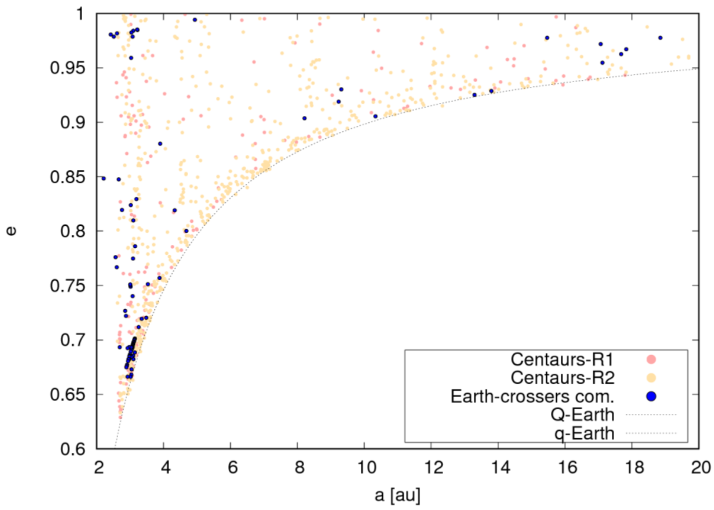

Figure 2.13: Earth encounters of Centaurs in comparison with real Near-Earth objects that can cross the Earth's orbit. Centaurs from Region 1 (R1, 13.11 au $\leq a \leq$ 30 au) and from Region 2 (R2, 5.5 au $\leq a <$ 13.11 au) are clones found in that region and are represented in light red and yellow. The orbits of real observed comets are represented with 'Earth crossers com.' in blue (Galiazzo et al., 2019).

3 Numerical Calculations

3.1 Dynamic Theory

Pluto is classified as a dwarf planet, and has a mass combined with its satellite Charon of $0.0022\,\mathrm{M}_{\oplus}$ ($\approx 0.179\,\mathrm{M}_{\mathrm{moon}}$)[1], which is small compared to that of the other planets of the Solar System, see Table 3.1.

Planet	**Mass in $M_{\oplus}$**
Mercury	0.0553
Venus	0.815
Earth	1.0
Mars	0.107
Jupiter	317.8
Saturn	95.2
Uranus	14.5
Neptune	17.1
Pluto	0.0022

Table 3.1: Mass of Pluto compared to the other planets in Solar System in Earth masses ($M_{\oplus}$) [2].

However, even weak perturbations by Pluto could influence less massive bodies leading to a change in their orbital elements. After a close encounter with the dwarf planet minor objects could reach areas influenced by stronger perturbations of the larger planets and could eventually reach the inner Solar System after evolving to Centaurs and Jupiter-family comets. Although Pluto could have only a minor contribution, it is still important to consider this possible evolution of trans-Neptunian objects to potentially hazardous Near-Earth objects. By performing numerical calculations with objects that cross the orbit of Pluto during their dynamical lifetime any possible influence that Pluto may have on these minor bodies is to be investigated. Fundamental for this study of a possible influence of Pluto on minor bodies is the restricted three-body problem.

[1] $1\,M_{moon} = 7.349 \times 10^{22}$ kg, Earth/Moon mass ratio = 81.3 (Horizon System - Horizon Web Application (https://ssd.jpl.nasa.gov/horizons/app.html/))
[2] https://nssdc.gsfc.nasa.gov/planetary/factsheet/planet_table_ratio.html

3.1.1 The Restricted Three Body Problem

The solution of the equations of motion of a Two-Body System (2BP) determines the nature of a system. In the 2BP a particle experiences the gravitational force of a second central mass and its motion can be calculated. However, the Three Body System can only be solved numerically, since no analytical solution to the system exists.

The Restricted Three Body Problem (R3BP) describes the gravitational interaction of three bodies, where the mass of the third one is significantly small, compared to the other two bodies. A lot of important mathematicians have dealt with finding a solution to the Three Body Problem, for example Euler, Laplace, Lagrange, Jacobi, Hamilton and Poincaré. In general, in a system containing of two bodies they move on circular, coplanar orbits about a central center of mass. When including the mass of a third body, that is significantly smaller, the problem of the motion of the third body becomes the circular restricted 3BP. The third smaller body, has no gravitational influence on the other two bodies and is therefore considered massless.

The R3BP provides a very good approximation for the masses in the Solar System and for specific configurations such as the motion of asteroids, planetesimals and dust. The two larger masses have constant separation and the same angular velocity, with the definition of a unit mass $\mu = G(m_1 + m_2) = 1$ with $m_1 > m_2$ it is possible to define $\bar{\mu} = m_2/(m_1 + m_2)$. For the system of unit the two masses now are $\mu_1 = Gm_1 = 1 - \bar{\mu}$ and $\mu_2 = Gm_2 = \bar{\mu}$, where $\bar{\mu} < 1/2$. For the coordinates in an inertial or sidereal system, and using the vector form of the inverse square law the equations of motion of a particle are defined as:

$$\ddot{\xi} = \mu_1 \frac{\xi_1 - \xi}{r_1^3} + \mu_2 \frac{\xi_2 - \xi}{r_2^3}, \tag{3.1}$$

$$\ddot{\eta} = \mu_1 \frac{\eta_1 - \eta}{r_1^3} + \mu_2 \frac{\eta_2 - \eta}{r_2^3}, \tag{3.2}$$

$$\ddot{\zeta} = \mu_1 \frac{\zeta_1 - \zeta}{r_1^3} + \mu_2 \frac{\zeta_2 - \zeta}{r_2^3} \tag{3.3}$$

where

$$r_1^2 = (\xi_1 - \xi)^2 + (\eta_1 - \eta)^2 + (\zeta_1 - \zeta)^2, \tag{3.4}$$

$$r_2^2 = (\xi_2 - \xi)^2 + (\eta_2 - \eta)^2 + (\zeta_1 - \zeta)^2 \tag{3.5}$$

These equations can also be used for the general 3BP since they do not include parameters about the path of the two masses. The bodies in the Solar System act as a system, which means that with a certain initial state it is possible to determine any future state with the result of the equations of motion. Hence a system where one can make calculations for the past or future with just the knowledge of its current state is labelled as a deterministic system. Any system where this condition is not fulfilled is therefore called chaotic (Murray and Dermott, 2000; Murray and Lissauer, 2007; Dvorak, 2013).

3.1.2 Close Encounters

Close encounters are essential for understanding the dynamical mechanisms that shaped the Solar System to how it is currently observed. Close encounters made accumulation of planetsimals possible that are needed for planetary formation while studying size and distribution of craters on surfaces of celestial bodies allows science to study the evolution of planetary surfaces and interiors. Close encounters influence the dynamical evolution of asteroids with planet crossing orbits and are responsible for the delivery of meteoritic material into the inner Solar System. Because of the Keplerian motion of a particle and the influence by large perturbations a three-body approximation does not work over long timescales.

Therefore, in 1976 Öpik formulated a theory of planetary close encounters based on the two-body approximation of crossing orbits, where to predict the outcomes of an encounter, the pre-encounter orbits must be given. The basic idea states that heliocentric orbits can be considered constant and Keplerian between encounters. During an encounter of the two bodies, the smaller one experiences a change in velocity identical to that given by two-body scattering as if the Sun has no effect during the encounter. (Carusi et al., 1990; Greenberg, 1982).

Close encounters of a particle and a planet can also be described by the Restricted Three-Body Problem. According to the Gauss's perturbation formulae (see Bertotti and Farinella (1990)) the evolution of e and a are related. This is consistent with the (approximate) conversation of the Tisserand invariant of this problem, which can be described by the model for the Restricted Three Body Problem. In the R3BP the Jacobi constant is conserved which means that the Tisserand-parameter does not change due to a close encounter (Galiazzo, 2013).

Tisserand Relation When a smaller body e.g. a comet, with initial semi-major axis a, eccentricity e and inclination i encounters a planet, for example Jupiter, these parameters change to a', e', i', whereas the Jacobi Integral stays constant. The Tisserand relation can be used to find out if a change in orbital elements, because of a close encounter with a planet happened for a previously undiscovered object and gives a good approximation for the motion where $e \neq 0$.

$$\frac{1}{2a} + \sqrt{a(1-e^2)}cosI = \frac{1}{2a'} + \sqrt{a'(1-e'^2)}cosI' \tag{3.6}$$

Especially in the evolution of the early Solar System, close encounters had an important influence on its structure (Murray and Dermott, 2000; Dvorak, 2013).

An example of a close encounter of Jupiter with a hypothetical comet that results in large changes of orbital elements of the comet is depicted in Fig. 3.1.

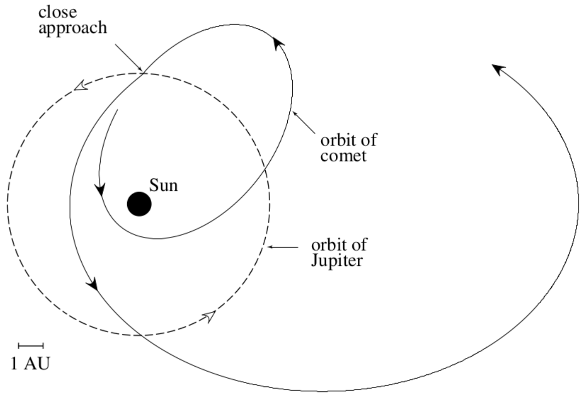

Figure 3.1: Illustration of an example of a close encounter of Jupiter with a hypothetical comet (Murray and Dermott, 2000).

3.2 Methodical Setup of Orbital Integrations

The aim of this study is it to investigate if Pluto perturbs minor bodies that cross its orbit. Therefore three different classes of minor bodies were considered: Plutinos, Centaurs and trans-Neptunian objects (TNOs). More precisely, Centaurs that have a aphelion distance larger than the perihelion distance of Pluto, which is $q = 29.762\,\text{au}$, as well as TNOs that have perihelion distance smaller than that of Pluto.

Objects categorized as Plutinos where found in the *"DATA"* section of the homepage of the *IAU - Minor Planet Center (MPC)*[3] under *"Orbits for TNOs, Centaurs and SDOs"* where a file called *"Distant.txt"* is provided. For description of the file see *"Guide to the Extended Versions of MPC Data Files Based on the MPCORB Format"*. Objects eligible for selecting as Plutinos where compared with the characterization in *JPL Small-Body Database Lookup*[4] and in *"List of Known Trans-Neptunian Objects"*[5]. Only objects that were labelled as Plutinos were chosen for the data sample.

The *JPL Small-Body Database Query*[6] was used to find Centaurs and trans-Neptunian objects that cross the orbit of Pluto. According to JPL Centaurs are defined as objects that orbit between Jupiter and Neptune (5.5 au $<$ a $<$ 30.1 au) and trans-Neptunian objects are described as objects that have orbits outside that of Neptune with a $>$ 30.1 au.

The ephemeris of every object, including planets and minor bodies, was generated with the *Horizon System Tool* provided by JPL[7] (set to 2459536.5 Julian Day Number). According to JPL an ephemeris is a tabulation of computed positions and velocities (and/or various derived quantities such as right ascension and declination) of an orbiting

[3]`https://minorplanetcenter.net/data`
[4]`https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html/`
[5]`https://www.johnstonsarchive.net/astro/tnoslist.html`
[6]`https://ssd.jpl.nasa.gov/tools/sbdb_query.html`
[7]`https://ssd.jpl.nasa.gov/horizons/app.html`

body at specific times[8].

In total, the orbital elements of 441 Plutinos, 158 Centaurs and 340 TNOs where integrated within a simplified Solar System (SSS) considering all planets from Venus to Neptune including the Pluto-Charon system, the mass of Mercury was added to the Sun. In addition, the same calculations were made in a SSS without Pluto for comparing the results of both measurements. Values of masses of the planets were also provided by JPL[9].

The minor bodies of the data sample used for the calculations are shown in Fig. 3.2, for better depiction the x-axis was cut off at 100 au.

The numerical calculations were performed with the Lie-integrator (Hanslmeier and Dvorak, 1984) which has an adaptive step size. Integration time was set to 50 Myr, accuracy parameter to 10^{-13} and the output step-size was selected with 2 kyr. In addition, a close encounter with a planet was considered occurring when a minor body is within one Hill radius from the perturbing body. See Table 3.2 for the Hill radii of the planets in the Solar System. The evolution of the orbital elements of all bodies during the integration are registered and considered until the minor body escapes or collides. An escape was considered when the body reaches $e > 0.99$ which means that it was sent on a hyperbolic orbit or when it evolved into negative values for semi-major axis. An object was considered to reach the inner Solar System when it showed a perihelion distance (q) smaller than 5 au. An example of the orbital evolution is depicted in Fig. 3.3 for Centaur *1998 TF35*, that also evolves into the inner Solar System and shows how its semi-major axis, perihelion distance, eccentricity, and inclination evolves during its dynamical lifetime.

The change in semi-major axis due to an encounter with Pluto was calculated with the difference in semi-major axis at the time step before and after the close encounter with $da = |a_{before} - a_{after}|$.

Planet	**Hill Radius**
	au
Venus	0.00671
Earth	0.00983
Mars	0.00658
Jupiter	0.33796
Saturn	0.41461
Uranus	0.45054
Neptune	0.77067
Pluto system	0.04015

Table 3.2: Hill radii of planets, including the dwarf planet Pluto with its satellites, which were considered as close encounter limiting distance.

[8] `https://ssd.jpl.nasa.gov/glossary/ephemeris.html`
[9] `https://ssd.jpl.nasa.gov/planets/phys_par.html`

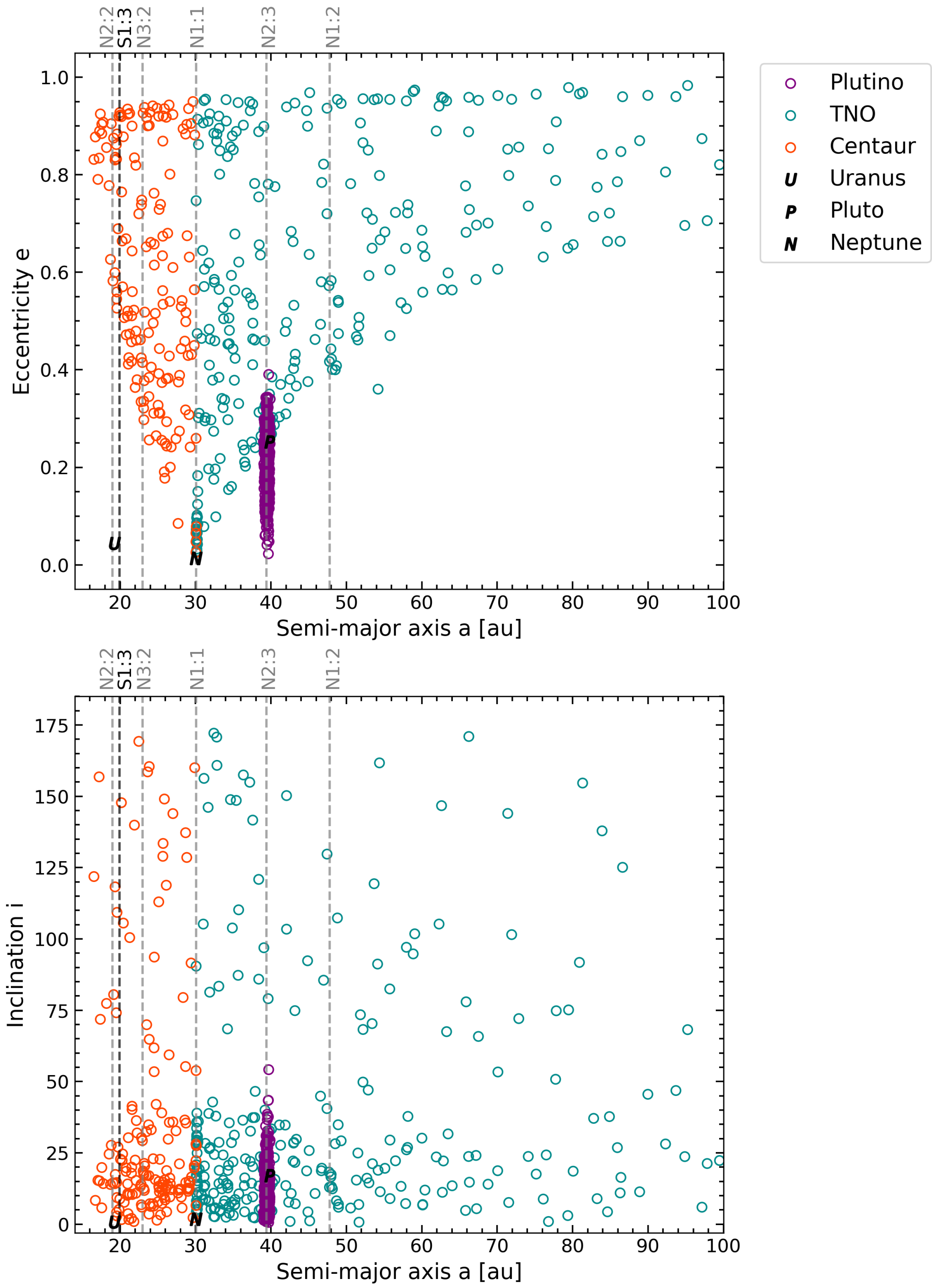

Figure 3.2: Data of sample of minor bodies located in a-e and a-i - space according to colors, where Plutinos are represented by purple, Centaurs by orange and TNOs by turquoise circles. Vertical lines represent Mean-Motion resonances (MMR) located in that area. Locations of the planets are represented by capital letters 'P' for Pluto, 'N' for Neptune and 'U' for Uranus.

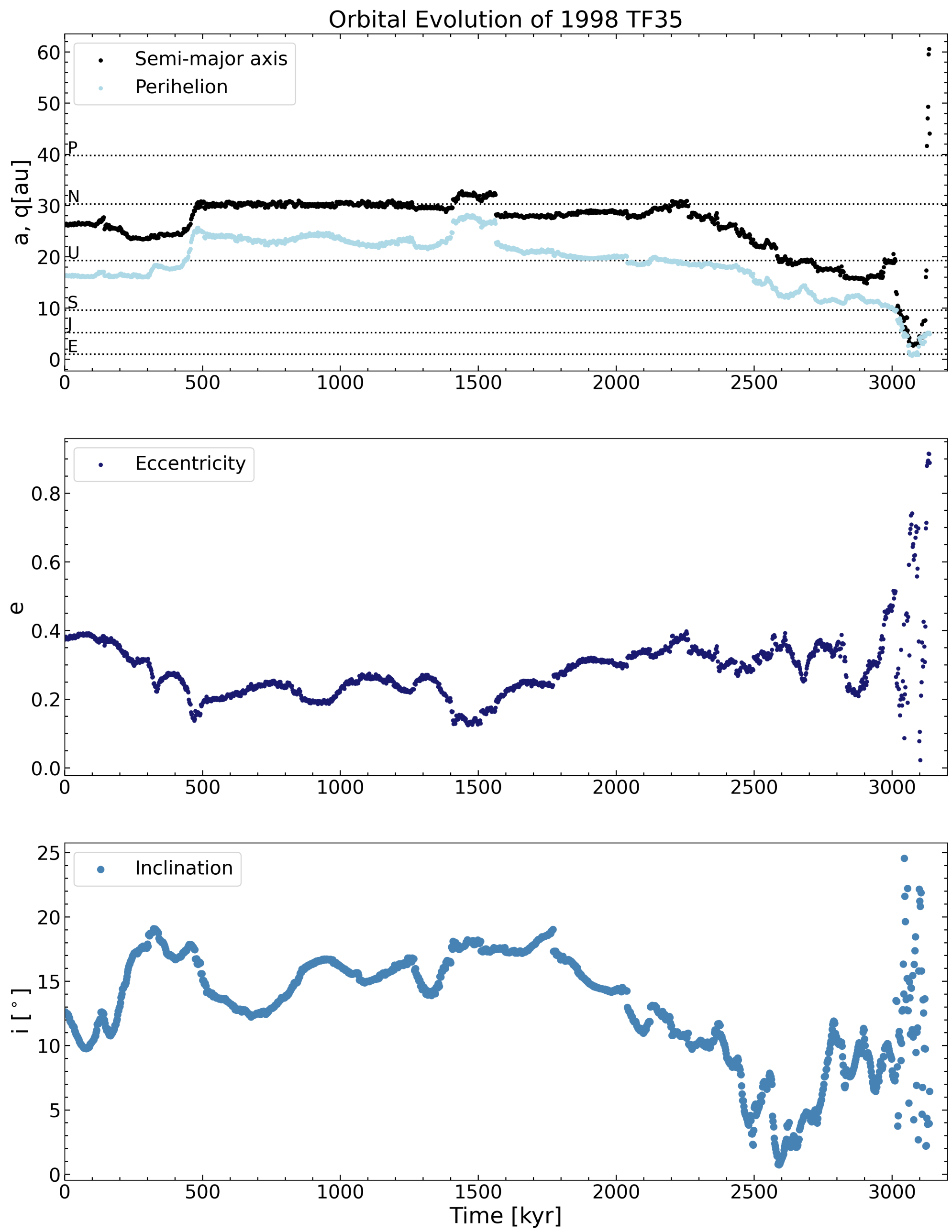

Figure 3.3: Example of the orbital evolution of Centaur *1998 TF35* until it leaves the Solar System. Semi-major axes of the planets are included and labelled according to their first letter.

Hill's Sphere In the circular, Restricted 3BP, the particle describes a Keplerian orbit most of the time, and can get perturbed via a close encounter with another larger object. In 1878 G. W. Hill described the motion of an object close to a second one with larger mass (in presence of the solar gravitation). The Hill's radius is a sphere of the radius with an equilibrium between tidal force and mutual attraction encircling the second mass (Murray and Dermott, 2000). His work was based on the work of E. Roche, therefore, the Hill's sphere can also be referred to as Roche-sphere. The Hill's sphere is an approximation for the gravitational sphere of influence around a larger object experienced by a much smaller object. It is located between the Lagrangian points L_1 and L_2, which lie along a line of centers of the two bodies. These points represent a limiting factor for the Hill's sphere. A third body orbiting the secondary mass at or just within the Hill's sphere would not stay stable on long terms (Gurfil and Seidelmann, 2016). For a celestial body with zero eccentricity the Hill's sphere is given by $r_h = (\mu/3)^{1/3}a$ which can be extended to $r_h \approx (\mu/3)^{1/3}a(1-e)$ calculated at the pericenter for any given eccentricity, where $\mu = m/M$ is the mass-ratio of the secondary mass and the primary mass (Hamilton and Burns, 1992).

Zero velocity curves or Hill' curves describe the motion of an object according to the Restricted Three Body Problem, which is characterized by the Jacobi integral, a natural integral of motion. Looking at the equilibrium points L_1 to L_5 different cases of topology of these zero velocity curves can be found depending on the critical value of the Jacobi Constant C_J and the mass ratio of the primary masses. These cases show that it is possible for an object to leave the Hill's sphere under given circumstances (Dvorak, 2013).

3.2.1 Orbital Integration with Lie-Integration Series

The motion of two bodies in the Solar System can be described by Newton's universal law of gravity, acting between two point masses. But the resulting system of differential equations can not be solved for more than two bodies. Therefore numerical integration codes are used to solve the Newtonian gravitational n-body problem in dynamical astronomy. Numerical integrations calculate the evolution of a system step-by-step, but the solutions only represent approximations for a given time interval (Eggl and Dvorak, 2010).

The Lie-integration method is named after Sophus Lie and was first tested as an application of a numerical tool by Hanslmeier and Dvorak (1984). Its basic idea is an infinitesimal transformation of the Hamiltonian system with respect to time. The Lie-integration method can be used for numerically solving differential equation like the equations of motion of n-body systems. The Lie-series is defined as

$$L(z,t) = \sum_{v=0}^{\infty} = \frac{t^\nu}{\nu!} D^\nu f(z) = f(z) + tDf(z) + \frac{t^2 D^2 f(z)}{2!} + ... \tag{3.7}$$

or

$$L(z,t) = e^{tD} f(z) \tag{3.8}$$

with D the Lie-operator, a linear differential operator defined as:

$$D = \Theta_1(z)\frac{\partial}{\partial z_1} + \Theta_2(z)\frac{\partial}{\partial z_2} + ... + \Theta_n(z)\frac{\partial}{\partial z_n} \tag{3.9}$$

where the point $z = (z_1, z_2, ..., z_n)$ lies in the n-dimensional z-space and the $\Theta_i(z)$ functions are holomorphic within a certain domain G.

In dynamical astronomy the Lie-integrator is an important tool to solve different problems in celestial mechanics like close encounters between celestial bodies (Dvorak, 2013).

3.2.2 Method for Plutinos Considered as Fugitives

The minor body group of the Plutinos was examined more closely than the group of Centaurs and trans-Neptunian objects. Since the Plutinos represent the bodies that most often come close to Pluto, close encounters between these objects are the most common and therefore the influence of Pluto on these objects can be investigated.

After the integrations with the Lie-integration method the average and the standard deviation of the semi-major axis of every Plutino was calculated. If that specific Plutino experienced a close encounter with Pluto only its development of the semi-major axis up to the first close encounter was used for these calculations. Whereas, if no close encounter happened between Plutino and Pluto the whole propagation of 50 Myr was considered for the determination of average and standard deviation of the semi-major axis of each of these minor objects. Then the average of these standard deviations of the semi-major axis of all 441 Plutinos was calculated and gives the critical value $\sigma_a = \Delta_{cut} = 0.190\,au$, whereas $3\sigma_a = 0.571\,au$.

Accordingly, a comparison between the integration with Pluto and without Pluto were made. Therefore the maximum deflection was calculated with the difference between the minimum and maximum of the semi-major axis (during the whole propagation time) and the average of the semi-major axis of a specific Plutino was determined with $\Delta a_1 = |a_{max,body} - a_{average,body}|$ and $\Delta a_2 = |a_{min,body} - a_{average,body}|$. As a result, any object with either Δa_1 or $\Delta a_2 > 3\sigma_a$ was considered a fugitive which gives the number of fugitives in comparison for Pluto and non-Pluto cases.

4 Results

4.1 Results of Numerical Data for Calculations with Pluto

To study the influence of the Pluto-system (including Charon) on minor bodies classified as Plutinos, Centaurs and trans-Neptunian Objects (TNOs) all close encounters between these bodies with the dwarf planet were considered. A close encounter took place when a minor bodies minimal distance to Pluto is within its Hill radius of 0.04015 au. According to this, 188 objects of all integrated 441 Plutinos were found to have at least one close encounter with Pluto which corresponds to 42.6%. Whereas in total these 188 Plutinos performed 261 close encounters with Pluto. Out of all 188 object that experienced a close encounter with Pluto, four were found that left the Plutino area which corresponds to 2.1%, for details see Table 4.1.

Object	**Semi-major axis**	**Eccentricity**	**Inclination**	**min. distance**	**da**
	au		*deg*	*au*	*au*
2015 VB165	39.757	0.2077	2.649	0.00023	0.792
2013 TR227	39.830	0.1682	21.420	0.02680	0.057
2014 UX229	39.899	0.3401	15.941	0.00933	0.236
2020 QH83	39.600	0.2547	22.448	0.02152	0.012

Table 4.1: List of Plutinos that had at least one encounter with Pluto and also left the area of the Plutinos. Listed are the initial orbital elements as well as the minimum distance between the body and Pluto during their close encounter and the change of semi-major axis due to a close encounter (da) in au.

In total 158 Centaurs were integrated with the Lie-integration method and 13 objects were found that performed one close encounter with Pluto which corresponds to 8.2%, see Table 4.2.

Of all 340 trans-Neptunian objects that were integrated 40 objects were found to have at least one close encounter with Pluto, which gives 11.8%. These 40 objects performed 59 close encounters with the dwarf planet, for detailed description of these TNOs see Table 4.3.

When summing up all objects of the Plutinos, Centaurs and TNOs in total 939 minor bodies were integrated with the Lie-integration method together with the Sun (+Mercury), all other planets and Pluto (+Charon). Out of all these objects 243 were found that complete at least one close encounter with Pluto. This means that 25.9% of all minor bodies experience at least one close encounter with Pluto.

Moreover, during a close encounter between a major and a minor body it comes to changes in the orbital elements of the minor body. Therefore the timestep before and

Object	**Semi-major axis**	**Eccentricity**	**Inclination**	**min. distance**	**da**
	au		*deg*	*au*	*au*
2002 CB249	26.600	0.5401	16.191	0.01160	0.078
2008 LC18	30.109	0.0786	27.508	0.02368	0.299
2014 UK70	22.486	0.7199	169.257	0.03274	0.121
2019 AB7	26.778	0.2417	12.111	0.03294	0.055
2014 NW65	23.267	0.5183	20.435	0.00431	0.062
1998 TF35	26.112	0.3814	12.634	0.03233	0.187
2001 KF77	26.181	0.2436	4.356	0.01233	0.099
2002 GB10	25.130	0.3920	13.313	0.02731	2.688
2014 JD80	25.524	0.2555	39.040	0.03251	0.348
2007 VL305	30.060	0.0650	28.090	0.01520	0.136
2015 XW379	27.732	0.3750	11.910	0.00271	0.448
2011 WG157	30.061	0.0258	22.281	0.02002	0.174
2013 MZ11	24.462	0.3109	6.3596	0.02239	0.049

Table 4.2: List of Centaurs that had one encounter with Pluto, for more detailed description see Tab. 4.1.

after the close encounter were considered for calculating the difference in semi-major axis (*da*, absolute value). These were noted for all minor objects that performed a close encounter with Pluto, for details see Table 4.1, 4.2 and 4.3.

Correspondingly, the diversity of these changes in semi-major axis (a) were depicted for all groups of concerning minor bodies in Fig. 4.1. It shows the distribution of the changes in the semi-major axis for Plutinos that leave the Plutino area (fugitives) after the integration, as well as for all close encounters performed by Plutinos, Centaurs and trans-Neptunian objects. That implies that the changes of a do not differ significantly from each other for all four groups depicted. In addition, it clearly shows that most of the objects complete only a minor change in a after a close encounter with Pluto. In the same way, the minimal distance between the minor bodies and Pluto was investigated. Here, too, the plot shows no noticeable deviations between the different groups. Although if only looked at the fugitive Plutinos they seem to have smaller minimal distances compared to the three other groups. While this may be true, one has to note, that all four groups show a great variation in sample size and therefore this plots should be considered as an approximate depiction of these results.

According to Öpik's theory formulated in 1976 a heliocentric orbit can be considered constant and Keplerian between encounters, whereas the minor object experiences a change in velocity during its encounter. Accordingly the relative velocity and the relative geometry can be established during an encounter. The result can be used to compute the planet-particle Rutherford-Scattering. Therefore one could argue that the scattering angle, or the change in semi-major axis (a) is inverse proportional to velocity squared and minimal distance between the particles, for more detailed explanation see Carusi et al. (1990) and Greenberg (1982). Because of this consideration it is interesting to determine whether there is a significant statistical correlation between the change of semi-major axis and the minimal distance during a close encounter. Therefore a Pearson correlation analysis was performed, separately, for fugitive Plutinos, as well as for all encounters of Plutinos, Centaurs and TNOs with Pluto. Before that, the data was searched for outliers, and these were eliminated. The outliers showed a very high change in semi-major axis which represents an exception compared to the majority of the cases. The results of this test are illustrated in Fig. 4.3 and show that the correlation is strong for fugitive Plutinos with the explanation that these objects have the smallest minimal distance. In other words, they approach Pluto the closest and therefore experience a bigger deflection. When considering all close encounters performed by the Plutinos with Pluto no correlation between minimal distance and change in a can be observed. However, when looking at Centaurs and TNOs that experience a close encounter with Pluto, a small correlation between the two parameters is depicted. As already mentioned before, due to large variation in the sample size of these groups of objects this analysis must be seen as an approximate evaluation.

Object	Semi-major axis	Eccentricity	Inclination	min. distance	da
	au		*deg*	*au*	*au*
2003 SS317	36.671	0.2405	5.896	0.03908	0.2658
				0.02649	0.0008
1996 AS20	35.738	0.6210	10.661	0.02731	0.1013
2000 YQ142	39.070	0.2774	23.798	0.01906	0.3292
1999 JB132	39.918	0.2787	13.041	0.03903	0.3584
2000 YB29	39.491	0.3091	7.702	0.03372	0.1020
2003 QO112	33.732	0.5047	6.956	0.02338	0.1470
2003 UC414	45.073	0.6366	25.825	0.03231	0.1895
2002 XJ91	39.346	0.2707	8.417	0.03104	0.0452
2005 GW210	39.348	0.2653	24.802	0.03946	0.1419
				0.01804	0.0029
				0.02236	0.0955
2004 MM10	42.541	0.3804	0.961	0.01197	0.0065
2005 EB299	51.680	0.5075	0.714	0.07249	0.3398
2014 DT112	47.433	0.7202	40.540	0.00945	0.1387
2015 AH281	37.577	0.4105	9.601	0.03151	0.1623
				0.03249	0.9867
2014 UA229	35.154	0.3786	31.244	0.03766	1.0975
2014 YY49	31.183	0.6063	20.420	0.01740	4.1258
2013 TS227	33.660	0.3225	24.274	0.01947	0.6190
				0.02475	0.1691
2016 SR105	46.682	0.5805	18.745	0.00453	0.0530
2015 QW23	33.122	0.5649	28.696	0.01990	0.2189
2015 VY184	85.936	0.7857	26.848	0.03296	0.3112
2015 VA166	48.032	0.4222	13.140	0.02183	0.3109
2021 DQ15	79.364	0.6494	3.035	0.02146	0.8240
2010 EN65	30.487	0.3109	19.246	0.02097	0.4441
				0.01857	0.0207
2010 TY53	39.155	0.4595	22.460	0.02344	0.3433
				0.02865	0.2015
2014 UT114	30.225	0.4744	15.216	0.01205	0.2158
2013 FJ28	34.969	0.4431	21.886	0.03855	0.2529
				0.01853	0.5479
2011 FY9	58.165	0.7386	37.791	0.03461	0.7659
				0.40085	0.1271
1998 BU48	33.108	0.3846	14.279	0.02816	0.4273
2005 TO74	30.245	0.0520	5.245	0.03818	0.0678
				0.01860	0.0052
2000 EE173	48.952	0.5382	5.948	0.03048	0.9583
2011 HM102	30.309	0.0836	29.335	0.01058	0.0941
2014 QO441	30.203	0.1017	18.845	0.03652	0.0238
2015 VV165	30.160	0.0852	16.845	0.02229	0.0268
				0.01856	0.1063
2015 RW277	30.156	0.7340	30.751	0.02489	0.3130
				0.01035	0.3049
				0.03293	0.3149
2014 UU240	30.167	0.0451	35.760	0.00568	0.0867
				0.02131	0.0303
2014 RO74	30.135	0.0504	29.514	0.02848	0.1568
2014 QP441	30.177	0.0663	19.417	0.03856	0.0013
				0.02192	0.3505
				0.02355	0.0453
2013 TK227	30.223	0.0814	18.612	0.03471	0.2599
				0.03898	0.0458
				0.02994	0.1028
				0.02131	0.1425
2014 SC374	30.151	0.0965	33.674	0.03736	0.0439
2015 VX165	30.107	9.0736	17.128	0.00390	0.0538

Table 4.3: List of TNOs that had at least one encounter with Pluto, for more detailed description see Tab. 4.1.

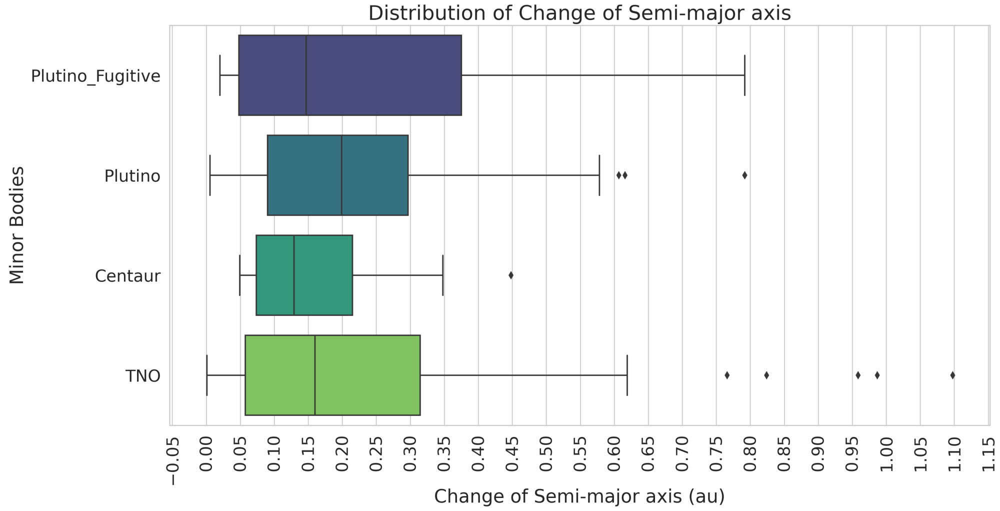

Figure 4.1: Boxplot of the distribution of the change of the semi-major axis due to a close encounter regarding fugitive Plutinos as well as all encounter performed between Plutinos, Centaurs and TNOs with Pluto. In a boxplot the center box represents the area where 50% of the data lies, the vertical bar shows the median value, whereas the minimum and maximum are depicted by the whiskers on the left and right side, respectively. Outliers are depicted as points outside of the whiskers.

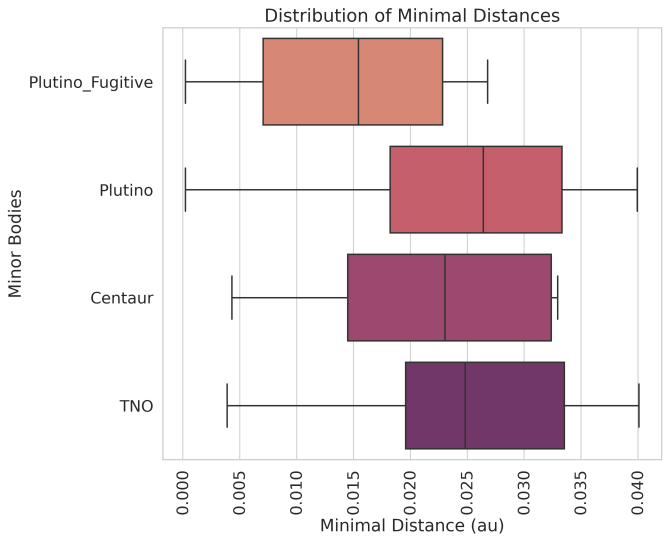

Figure 4.2: Distribution of minimal distances during a close encounter between minor bodies and Pluto, for detailed description see text above.

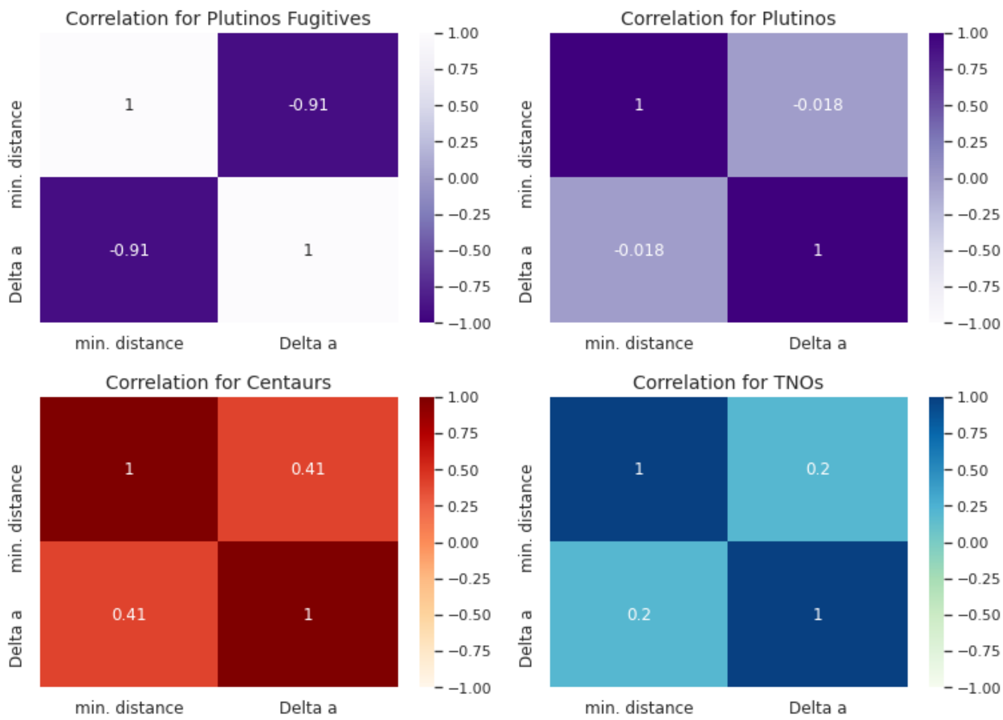

Figure 4.3: Results of the Pearson's correlation analysis between the minimal distance and the change of a for fugitive Plutinos, all Plutinos, Centaurs and trans-Neptunian objects seperately, where minimal distance is $min.distance$, change of semi-major axis is $\Delta a = \text{da}$. Any outliers were eliminated before the analysis.

4.2 Investigation of the Influence of Pluto on the Plutinos

The integration of 441 Plutinos with the Lie-integration method in a simplified Solar System (SSS) with Pluto revealed four fugitives of the Plutino area, which were described in the section above. These four objects left the Plutino area (3:2 MMR) as a result of perturbations of either Pluto or Neptune. In comparison, for cases that were integrated without Pluto only two fugitives were found which were *2014 UX229* and *2020 QH83* which are also fugitives for cases integrated with Pluto listed in Table 4.1.

The results of the numerical integration also showed that the Plutinos performed the majority of close encounters with Pluto, as they are also the group of objects most commonly found in its vicinity. In total 441 integrated Plutinos performed 261 close encounters with Pluto.

In addition, to determine how many fugitives can be found in a system integrated with or without Pluto a comparison regarding the difference between minimum and maximum of their semi-major axis and the average of the semi-major axis was calculated, which gives the maximum deflection of each object (for more detailed description read section 3.2.2). Accordingly, a Plutino was considered a fugitive if its $\Delta a_{1,2}$ is larger than $3\sigma_a = 0.571\,\mathrm{au}$ for both cases with and without Pluto. As a result, 137 fugitives of total 441 Plutinos that were integrated were found in the integration with Pluto. Which means that 31.1% of all objects can be considered as fugitives in a system that included Pluto. Whereas in the integration that excluded Pluto 124 objects were found of the total 441 with a Δa larger than 0.571 au, which corresponds to 28.1% that are determined as fugitives. A comparison of objects considered as fugitives in a system with and without Pluto is illustrated in Fig. 4.4 and 4.5. It can be seen that there exist slightly more fugitives in a system integrated with Pluto. For a more significant result, it should be considered to extend the sample size of Plutinos. In addition, for better comparison the same method can be used for investigating other groups of minor bodies that perform close encounters with Pluto like Centaurs and TNOs, but this would be beyond the scope of this work. However, this method could be useful to investigate how many Plutinos will survive from now on with different tools. Or in other words, could be useful to find the lifetime of present Plutinos.

Figure 4.6 depicts $\Delta a_{1,2}$ or the maximum deflection of all integrated Plutinos for cases with Pluto and without Pluto as well as for cases only larger than $3\sigma_a$. For better visualisation of the results any outliers were eliminated.

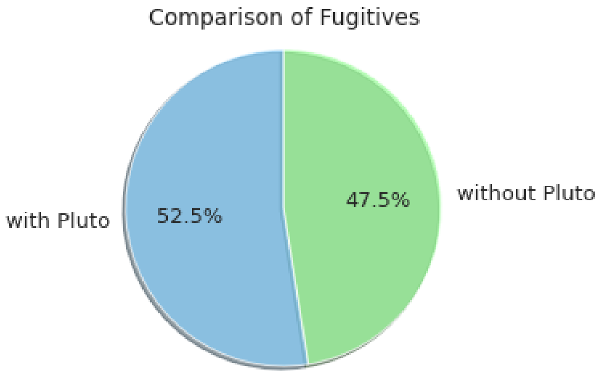

Figure 4.4: Results of analysis of Plutinos that can be considered as fugitive for systems with and without Pluto. Of all 261 fugitives 52.5% were found in the system integrated with Pluto, and 47.5% in the system without Pluto.

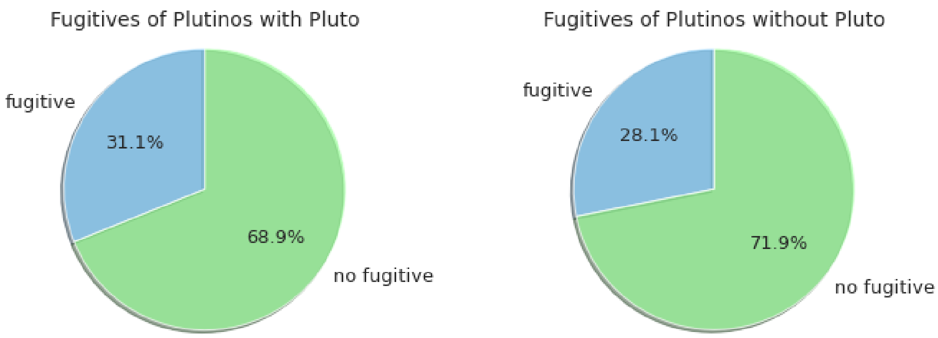

Figure 4.5: Percentage of fugitives in a system with and without Pluto, in comparison to all integrated 441 Plutinos. 31.1% of all objects are fugitives in a system with Pluto, whereas 28.1% are determined as fugitives in a system without Pluto.

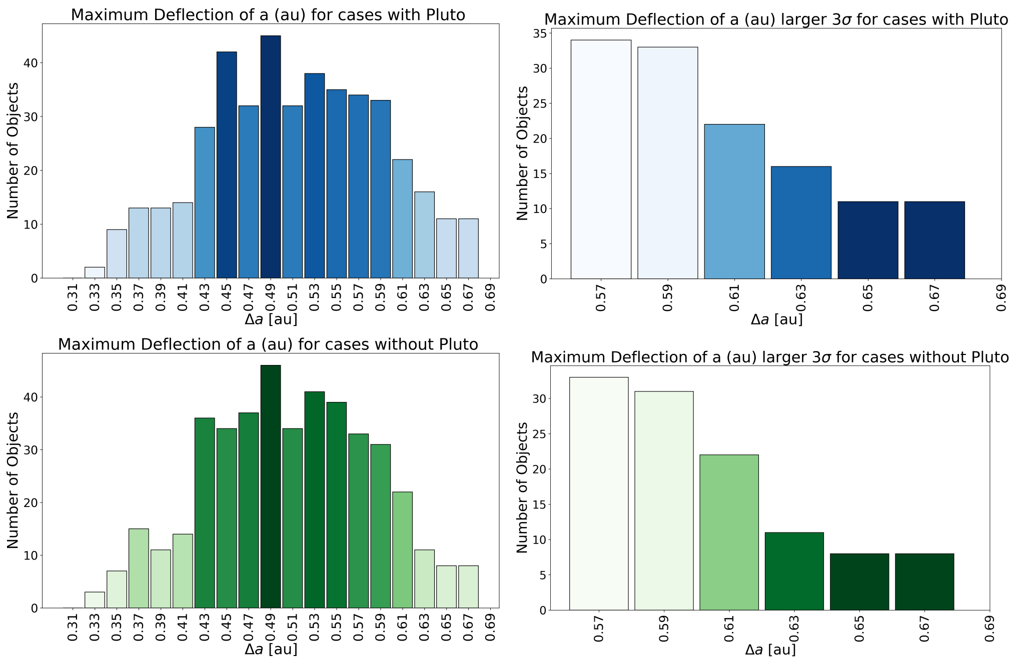

Figure 4.6: Comparison of the maximum deflection of all Plutinos in a system with and without Pluto. The upper left plot depicts the maximum deflection for all Plutinos with Pluto, whereas the upper right plot shows the maximum deflection of only objects that are regarded as fugitive in a system with Pluto. A fugitive was considered any object that had $\Delta a_{1,2}$ (in plot only Δa) larger than 0.571 au ($3\sigma = 3\sigma_a$). The two lower plots show the same comparison for cases integrated without Pluto.

4.3 Investigation of Orbital Evolution and Close Encounters

The orbital evolution for each minor body is very individual and depends on various factors such as gravitational influence of larger bodies as well as deflection due to close encounters. Obviously the trajectory of different minor bodies can become very chaotic after close encounters with the planets. Considering the orbital evolution of minor bodies it was investigated whether Pluto has any influence on changing the trajectory of a body as a consequence of a close encounter between the two bodies. In addition, since it is possible for minor bodies to evolve through the Centaur zone into the terrestrial planet (TP) region and with that could become a Near-Earth Asteroid (NEA) that could be potentially dangerous for life on Earth, it was investigated how many objects reach the TP-region in a system with and without Pluto.

4.3.1 Orbital Evolution of Plutinos with and without Pluto

In total 441 Plutinos were integrated of which four (*2015 VB165, 2015 TR227, 2015 UX229* and *2020 QH83*) were found to leave the Plutino area after a close encounter with Pluto. In their following orbital evolution three Plutinos evolved to Centaurs at some point in their lifetime after the close encounter, and one became a Trans-Neptunian object. However, two Plutinos (*2015 UX229* and *2020 QH83*) are found to leave the Plutino area in a system integrated without Pluto. One of these objects evolved to a Centaur during its lifetime and ended up as TNO, and the other one became and stayed a TNO. Quite interestingly one of these two Plutinos also reached the terrestrial planet region with a minimal perihelion distance $q = 2.585$ au.

To compare cases with and without Pluto one has to have in mind, that in cases with Pluto, the evolution after its first encounter with Pluto was investigated considering its change in population. Whereas for integration of a system without Pluto, the whole dynamical lifetime until end of integration time or escape of the object was considered. Furthermore, most of the objects also experience close encounters with other planets, which were not included in these comparison.

The detailed evolution is listed in Table 4.4, whereas the table reads as followed: the first line represents the cases integrated with Pluto and the second line shows the same object integrated without Pluto. It lists the time of the first encounter (kyr) as well as the corresponding semi-major axis (does not exist for cases without Pluto), the time it becomes a TNO or a Centaur, and a tick-symbol if it propagates some time between Centaur-zone and TN-Region. In addition, its minimal semi-major axis (au) during its whole dynamical lifetime is listed and if this object finds its way in the terrestrial planet region the perihelion distance (au) is given (TR), as well as its escape time or the end of integration time (End).

Examples of Orbital Evolution of Escaping Plutinos

The Plutino *2016 VB165* remains a Plutino for about 15.6 Myr and after its first considerable close encounter with Pluto becomes chaotic with a change in semi-major

Object	Encounter *ky/au*	TNO *ky*	Centaur *ky*	C/TNO	min. a *ky/au*	TR *ky/au*	End *ky/au*
2015 VB165	15626.727	15638.0	21788.0	✓	23196.0	-	50000.0
	40.228				21.464	-	50.013
	-	-	-	-	-	-	-
2013 TR227	42089.247	x	45078.0	✓	47606.0	-	48630.0
	45.738				14.015	-	863.592
	-	-	-	-	-	-	-
2014 UX229	43737.866	x	x	x	49896.0	-	50000.0
	45.428				37.608	-	38.394
	-	12122.0	36266.0	x	49830.0	49830.0	50000.0
					4.227	2.5854	18.007
2020 QH83	38752.011	x	49394.0	x	49744.0	-	50000.0
	36.449				23.040	-	24.616
	-	49454.0	x	x	48534.0	-	50000.0
					38.823	-	42.473

Table 4.4: List of the orbital evolution of Plutinos that leave the Plutino area in cases for a system with Pluto (first line) and without Pluto (second line) for each object, for detailed description see text above.

axis of $da = 0.7918$ au with a corresponding minimal distance of 0.0002357 au. During its dynamical lifetime it also experiences close encounters with Uranus and evolves into the Centaur-zone. After its chaotic phase the body remains in the trans-Neptunian region. For detailed orbital evolution steps see Table 4.4 and for visualisation see Fig. 4.7. Figure 4.8 shows a zoom of the close encounter between *2016 VB165* and Pluto. The object was not found to leave the Plutino area in calculations without Pluto.

Another good example is Plutino *2014 UX229* which remains a Plutino for about 41 Myr, when it suddenly becomes chaotic after a close encounter with Neptune and stays chaotic after repetitive encounters with Neptune within the trans-Neptunian region. As depicted in Fig. 4.9 the first considerable close encounter with Neptune happens at about 41.9 Myr which results in an important change in semi-major axis considering the difference between the timestep before and after the close encounter of $da = 4.4722$ au. Similarly the close encounter between the Plutino and Neptune with the smallest minimal distance of 0.05974 au at about 49.4 Myr results in a major change of semi-major axis with $da = -22.981$ au. For comparison, one close encounter appears with Pluto at 43.7 Myr and a minimal distance of 0.00934 au which results in a da of only -0.2362 au.

In comparison, the orbital evolution for the same Plutino calculated in a system without Pluto, where the first considerable close encounter takes place much earlier at about 11.8 Myr. This also results in a chaotic trajectory where the object evolves into the Centaur zone between about 36.3 to 38.6 Myr with close encounters with Uranus and again between 49.4 Myr and 49.5 Myr with additional encounters with Saturn, where *2014 UX229* reaches a minimal semi-major axis of 4.22 au which corresponds to a perihelion distance of $q = 2.585$ au which means that this object enters the terrestrial planet region. At the end of a very chaotic phase it leaves the Solar System.

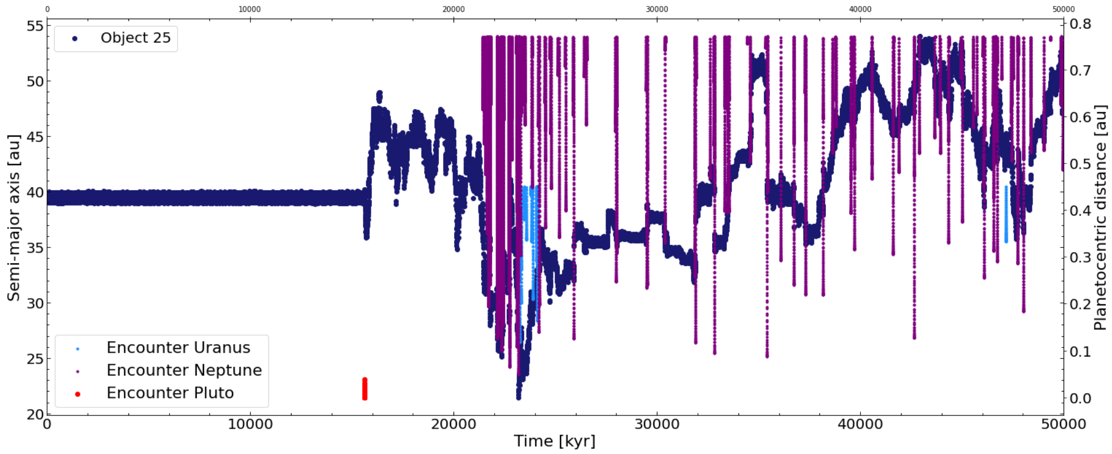

Figure 4.7: Orbital evolution of Plutino *2016 VB165* with the time on the x-axis in kyr, the left y-axis shows the semi-major axis in au, and the right y-axis the minimal distance in au between major and minor body which indicates the close encounter between the two bodies. In violet the close encounters with Neptune are depicted and in red the ones with Pluto, blue shows close encounters with Uranus.

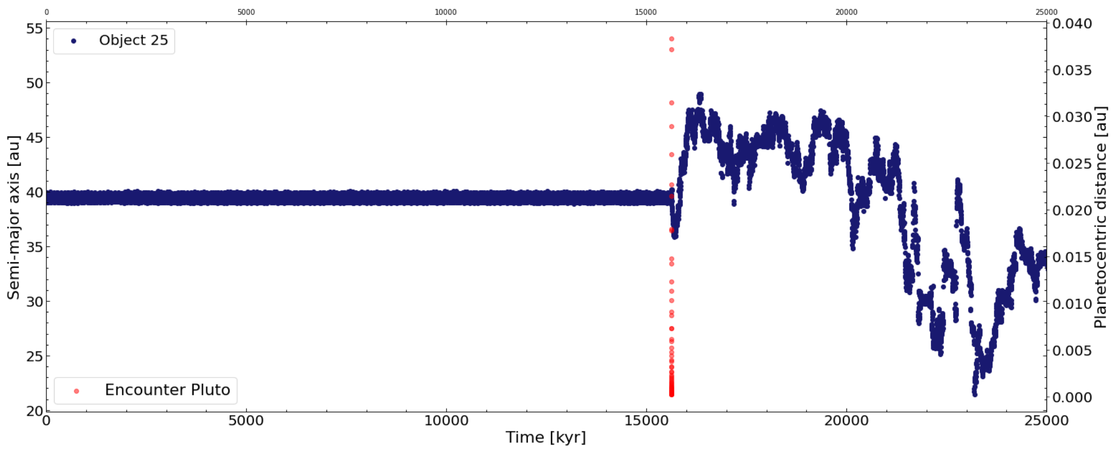

Figure 4.8: Zoom of the close encounter between *2016 VB165* and Pluto.

4.3.2 Orbital Evolution of Centaurs with and without Pluto

13 Centaurs out of 158 were found to have one close encounter with Pluto. Ten of these objects were found to leave the Centaur area, at some point during their dynamical lifetime. Comparison of the evolution of objects integrated with and without Pluto is rather difficult, because Centaurs tend to have a very chaotic behavior and often repeatedly propagate between the Centaur zone and trans-Neptunian region. For a detailed list see Table 4.5, which can be read the same as in the section above. However, quite surprisingly

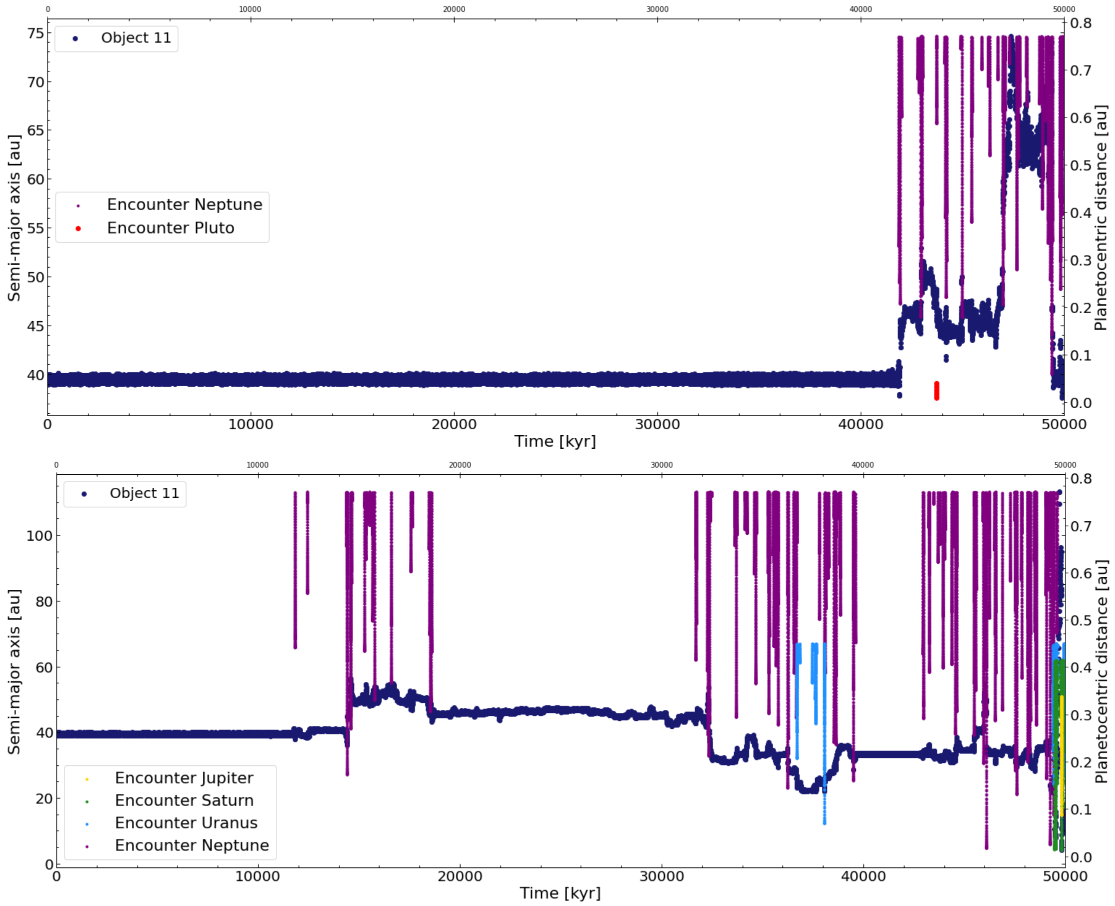

Figure 4.9: Orbital evolution of Plutino 2014 UX229 where the upper plot shows the orbital evolution in a system with Pluto, whereas the lower plot shows it without Pluto. In violet the close encounters with Neptune are depicted and in red the ones with Pluto, blue show the ones with Uranus, green with Saturn and yellow with Jupiter.

there were five cases (*1998 TF35, 2001 KF77, 2015 XW379, 2013 MZ11, 2002 GB10*) found in the integration without Pluto of Centaurs that reach the terrestrial planet region. Whereas in a system integrated with Pluto only two were found (*2014 UK70, 1998 TF25*). It would be interesting to study if the missing gravitational influence of Pluto could be responsible for this development. In other words, whether Pluto might work as a kind of protector for the terrestrial planet region from incoming Centaurs, because it possibly sends these objects on trajectories away towards the trans-Neptunian region. But this is very speculative and must be investigated in the future to find proof for such a behavior.

One example for a Centaur that reaches the terrestrial planet region is *1998 TF35* which reaches a minimal semi-major axis of 2.678 au at 3.076 Myr and a perihelion distance of $q = 0.725$ au at 3.072 Myr and leaves the system at 3.138 Myr integrated in a system with

Object	Encounter *ky/au*	TNO *ky*	Centaur *ky*	C/TNO	min. a *ky/au*	TR *ky/au*	End *ky/au*
2002 CB249	15621.020	19200.0	19798.0	✓	1116.0	-	50000.0
	25.509				20.432	-	57.675
	-	56.0	594.0	x	3948.0	-	4562.0
					18.725	-	837.620
2014 UK70	213.399	2996.0	x	x	148.0	11242.0	252.0
	22.590				22.319	2.193	248.086
	-	3812.0	8158.0	x	218.0	-	8394.0
					18.693	-	29.326
2019 AB7	46280.0	✓	49223.9	x	402.0	-	50000.0
	37.160				26.091	-	34.863
	-	1776.0	8524.0	✓	416.0	-	50000.0
					20.202	-	32.901
2014 NW65	23.975	5522.0	x	x	5340.0	-	6634.0
	22.685				15.667	-	761.613
	-	1560.0	2868.0	✓	14734.0	-	17996.0
					14.962	-	647.640
1998 TF35	366.110	1408.0	1564.0	x	3076.0	3072.0	3136.0
	24.210				2.678	0.7251	44.076
	-	3152.0	23112.0	✓	27334.0	27336.0	27712.0
					3.111	1.386	913.658
2001 KF77	1791.234	3554.0	x	x	3316.0	-	3906.0
	25.396				10.103	-	783.088
	-	1462.0	1592.0	x	2298.0	2298.0	2308.9
					4.076	1.410	37.193
2002 GB10	3720.0	✓	x	x	926.0	-	12436.0
	92.014				14.837	-	857.540
	-	7310.0	x	x	7304.0	-	7396.0
					7.865	-	327.215
2014 JD80	13214.291	19112.0	20866.0	x	26634.0	-	34993.0
	26.864				15.624	-	25.816
	-	12670.0	13138.0	✓	42320.0	-	46882.0
					14.817	-	51.862
2015 XW379	38429.729	✓	x	x	1406.0	-	50000.0
	54.0381				18.554	-	52.267
	-	664.0	1180.0	✓	2764.0	2764.0	2910.0
					4.258	2.334	326.937
2013 MZ11	48599.906	✓	x	x	116.0	-	50000.0
	39.116				22.533	-	39.840
	-	3522.0	x	x	3290.0	3288.0	3544.0
					5.067	1.647	238.541
2002 GB10	7720.787	✓	x	x	926.0	-	12436.0
	87.374				14.837	-	857.540
	-	7310.0	x	x	7304.0	7322.0	7396.0.0
					7.865	4.740	327.215

Table 4.5: List of Centaurs that had one close encounter with Pluto and left the Centaur zone and objects that reach the inner planetary region.

Pluto, see Fig. 4.10. Compared with a system that excluded Pluto it reaches a minimal semi-major axis of 3.111 au and perihelion distance of 1.385 au during its dynamical lifetime of about 27.7 Myr.

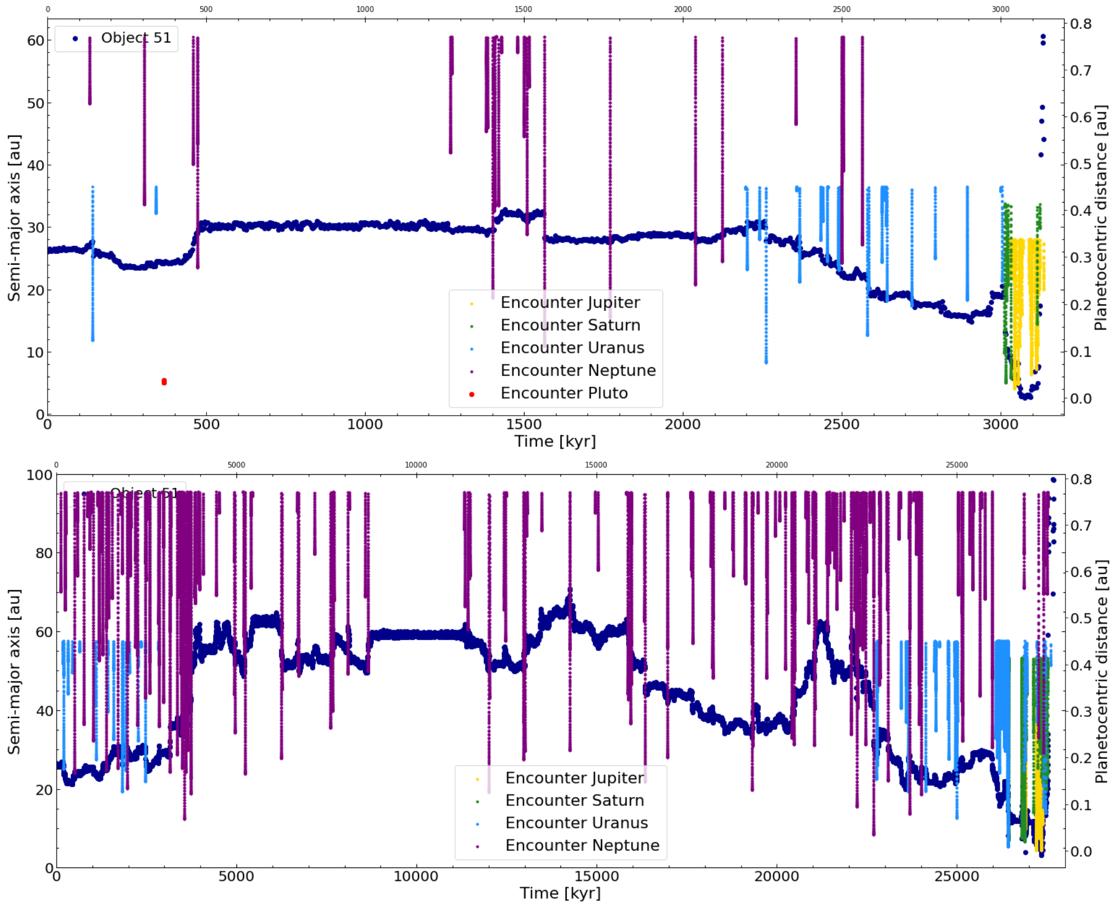

Figure 4.10: Orbital evolution of Centaur *1998 TF35*, description same as figures before.

4.3.3 Orbital Evolution of Trans-Neptunian Objects with and without Pluto

In total 340 trans-Neptunian objects were integrated and 40 are found that have at least one close encounter with Pluto. Of those 40 objects 28 objects ramain in the TN-Region after the close encounter with Pluto, whereas 12 evolve into the Centaur zone. However, in a system that excluded Pluto a similar amount of 27 objects are found that stay a trans-Neptunian object and 13 evolve into the Centaur Zone. Also here it must be considered that the evolution of an object was looked at after the close encounter with Pluto and the whole integration time was regarded for the same objects that were integrated without Pluto. In addition, the results showed that in scenarios with Pluto three objects found their way into the terrestrial planet region. Whereas in a system integrated without Pluto four TNOs were found to enter the inner Solar System. For detailed comparison see Table 4.6, which reads as in the sections above. Listed are TNOs that leave the trans-Neptunian region sometime during their dynamical lifetime after a close encounter with Pluto, and TNOs that evolve into the terrestrial planet region in cases integrated with and without Pluto. It seems that overall there is no large difference between the system with and without Pluto, but this should be investigated further.

TNO *2014 UT114* reaches a minimal semi-major axis of 4.299 au and a perihelion distance of $q = 1.899$ au at 14.5 Myr. Figure 4.11 depicts the orbital evolution of *2014 UT114* which reaches the inner Solar System at the end of its dynamical lifetime before it leaves the Solar System after the semi-major axis increases again. In contrast, the same object in a system without Pluto primarily shows an increase in semi-major axis until it leaves the Solar System.

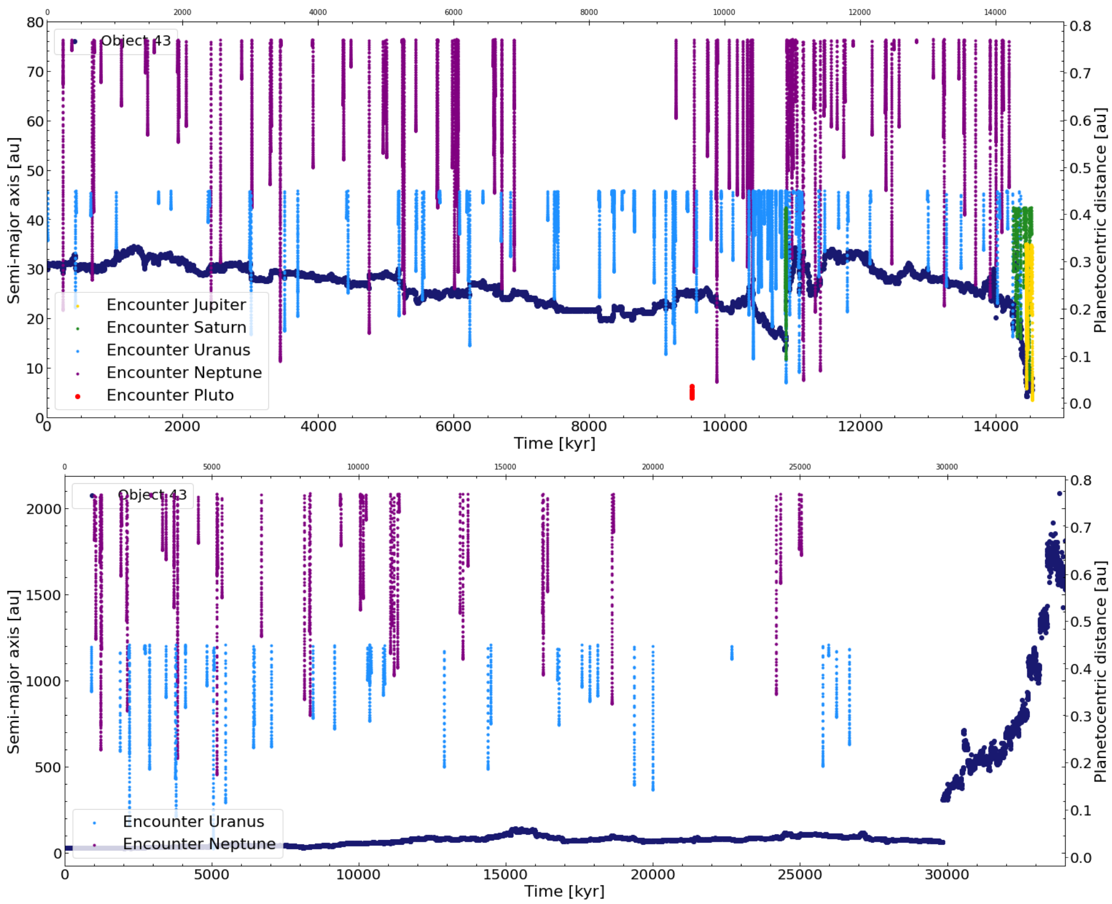

Figure 4.11: Orbital evolution of TNO *2014 UT114* where the upper plot shows the orbital evolution in a system with Pluto, and the lower plot shows it in a system without Pluto. Close encounters are color coded red for Pluto, violet for Neptune, blue for Uranus, green for Saturn and yellow for Jupiter.

Object	Encounter	Centaur	C/TNO	min. a	TR	End
	ky/au	*ky*		*ky/au*	*ky/au*	*ky/au*
1996 AS20	13973.851	21790.0	✓	39838.0	39836.0	40104.0
	53.896			5.499	2.800	46.694
	-	x	x	1328.0	-	50000.0
				32.241	-	52.152
1999 JB132	18936.912	48744.0	✓	48798.0	-	50000.0
	52.043			28.891	-	34.2075
	-	x	x	4980.0	-	50000.0
				33.827	-	51.351
2003 QO112	26733.944	27544.0	✓	40832.0	-	41828.0
	33.835			10.047	-	1066.788
	-	1210.0	✓	1428.0	-	50000.0
				27.304	-	66.478
2003 UC414	33497.145	43632.0	✓	43632.0	-	50000.0
	39.920			22.684	-	41.2715
	-	x	x	5266.0	-	49085.9
				36.102	-	1046.971
2004 MH10	8451.073	x	x	7264.0	-	50000.0
	34.329			29.976	-	95.654
	-	1708.0	✓	6038.0	6038.0	6432.0
				4.445	3.141	622.232
2005 EB299	18375.984	27088.0	✓	30566.0	-	50000.0
	45.908			19.416	-	31.363
	-	2848.0	x	8606.0	8606.0	13268.0
				4.947	3.824	1003.255
2013 TS227	39300.003	x	x	35126.0	35126.0	50000.0
	39.812			5.809	3.690	38.9447
	-	642.0	✓	8702.0	-	50000.0
				20.381	-	64.316
2014 UA229	27989.908	48816.0	x	9234.0	-	50000.0
	42.161			24.402	-	32.653
	-	x	x	48816.0	49849.9	50000.0
				5.749	3.221	65.252
2021 DQ15	30210.117	39532.0	✓	46016.0	-	46636.0
	37.187			11.776	-	301.948
	-	x	x	35385.9	-	50000.0
				42.121	-	44.137
2010 EN65	4704.463	5590.0	✓	3010.0	-	50000.0
	42.760			21.626	-	32.007
	-	6468.0	✓	7260.0	-	50000.0
				26.501	-	59.626
2014 UT114	9513.720	x	✓	14450.0	14530.0	14538.0
	25.424			4.299	1.899	610.826
	-	126.0	✓	2024.0	-	33164.0
				27.589	-	1326.797
2013 FJ28	11255.576	12228.0	✓	49998.0	-	50000.0
	33.803			19.501	-	19.562
	-	596.0	✓	32772.0	32782.0	32810.00
				4.852	2.857	2797.746
1998 BU48	30736.826	30736.0	✓	47804.0	-	50000.0
	41.327			10.013	-	57.012
	-	1298.0	✓	1298.0	-	32810.00
				15.519	-	61.108
2015 RW277	4072.476	31994.0	x	33230.0	-	50000.0
	29.916			27.942	-	42.559
	-	30944.0	x	32452.0	-	50000.0
				24.885	-	38.175

Table 4.6: List of trans-Neptunian objects that evolve into the Centaur zone after a close encounter with Pluto and objects that reach the terrestrial planet region.

5 Discussion

Theoretical models and their verification using methods such as numerical simulations should be supplemented with observations in order to confirm existing knowledge and theories, but also to examine new processes and hypotheses regarding the formation and evolution of our Solar System. In addition, one can expect that the methods and thus also the results of these investigations will continue to improve over the next few years, since new observational results from various space missions will be incorporated as technology advances. Therefore, it is also useful to compare different studies with the same thematic research background and what they can conclude from their investigations.

5.1 Comparison with Previous Studies

This shows a selection of studies of investigations regarding the 2:3 MMR with Neptune and the consequences of a particles leaving that area, for more details see Di Sisto and Rossignoli (2020).

A study carried out by Morbidelli (1997) found that the 2:3 MMR with Neptune is a slow chaotic diffusion zone. Therefore encounters between Neptune and bodies within that resonance should be an active source of current Centaurs and Jupiter-family comets (JFCs). His results showed that only 10% of the Plutinos in this weakly chaotic zone are found to have encounters with Neptune in the last 1 Gyr.

Tiscareno and Malhotra (2009) performed numerical integrations to study the long term chaotic dynamics of the 2:3 MMR ($a \sim 39.4$ au) of the Plutinos and the 2:1 MMR ($a \sim 47.7$ au) of the Twotinos. The dynamics of these bodies and the structure of these resonances could provide a mechanism for preserving a population over the age of the Solar System. In addition, the dynamical evolution of these particles to orbits where they experience encounters with Neptune was investigated as well as their way into the inner regions of the Solar System. The main subject of this study was the estimation of the population of Plutinos and Twotinos about 4 Gyr ago. An additional aim was it to find the effects of Pluto on the Plutino population, and how bodies that escape the MMR behave. Therefore, they performed numerical integration with the "Swift skeel" mixed variable symplectic N-body integrator for 1 Gyr. The initial conditions of the particles where chosen to represent a suitable coverage of the chosen resonance zones. In all their runs the authors included the four giant planets into the gravitational field of the Sun. To study the influence of Pluto they performed the same integration with and without the dwarf planet as massive perturber. The authors assumed that the chaotic evolution of the proper elements can be approximated with a diffusion process. The rate of which they disperse is represented by a diffusion coefficient $D = \langle(\Delta a)^2\rangle/\Delta t$ where

Δa is the change in proper semi-major axis over interval of time Δt, the mean was taken over a sample of particles. With a set of about 1331 Plutinos and 1445 Twotinos they performed a 1 Gyr integration. A Plutino escapes the resonance if its semi-major axis is either below 38.77 au or larger than 40.17 au which lies at ± 0.7 au from their central resonant value. Tiscareno and Malhotra (2009) found that Pluto's influence is resulting in a $\sim 4\%$ decrease in Plutino population that survive the projected 4 Gyr integration time. At the end of 4 Gyr 27% survived for 4 Gyrs in the calculations with Pluto (extrapolation of 1 Gyr integration) and 28% in the system without Pluto. In addition, these fugitive Plutinos spend about half their lifetime as Centaurs and half of it as Scattered-Disk objects (SDOs). 27% of the fugitive objects are found to enter the inner Solar System (heliocentric distance $r < 5$ au).

Another study by de Elía et al. (2008) researched the collisional and dynamical evolution of Plutinos, which represents another way for objects to leave the resonance. In their simulations with the simplectic code "EVORB" they included a Pluto-sized object located at 2:3 MMR with Neptune. They performed integration with 197 Plutino candidates, in a system including masses of the terrestrial planets added to the Sun as well as the four giant planets and Pluto. The results show that 1 ecliptic comet with a diameter larger than 1 km leaves the 2:3 MMR every 300 - 1200 yrs. Or in other words, a flux rate of escape of 0.5% of Plutinos in 10 Gyr, which is much less than the dynamical removal (Di Sisto and Rossignoli, 2020).

In Di Sisto and Rossignoli (2020) the authors used their results of Di Sisto et al. (2010) to compute the rate of Plutinos that reach the Centaur zone ($a < 30$ au). They found that 80% of the Plutinos that leave the resonance find their way into the Centaur zone.

In addition a study by Galiazzo et al. (2016) performed numerical simulations of the orbital evolution of Centaurs and trans-Neptunian objects and their influence on the Main belt of asteroids located at $1.78 \leq a \leq 3.8$ au. The simulations were performed with the Lie-integration method in a system including planets from Venus to Neptune. A close encounter was assumed when the body was within 0.0024 au from the perturbing body. A sample of clones of observed Centaurs and TNOs with a diameter larger than 100 km was investigated for their orbital evolution over 50 Myrs. The results show that 240 Centaur clones out of 1023 in total enter the Main belt, which equals 23% as well as 73 TNOs out of 2871, which are 3%.

The main result of this thesis is the comparison of fugitive Plutinos in a system with and without Pluto. Therefore, of all 441 Plutinos that were integrated for 50 Myrs, the maximum deflection of their dynamical lifetime was calculated. A Plutino was considered as a fugitive if its deflection in semi-major axis was larger that 0.571 au. It was shown that 31.1% left the resonant area in a system with Pluto. Which on the contrary means that about 70% of the population survived. It can be seen compared with previous studies, that the amount of Plutinos leaving the area is significantly smaller. This could be due to reasons of methodical choices or to different assumptions that were made regarding the size estimation of current and ancient Plutino population. In addition it was found that in the integration without Pluto 28.1% of the Plutinos left the resonance. Which means that also here Pluto seems to have only a moderate influence of decreasing the

Plutino population of about 3%, which is quite similar to previous findings. To receive a more significant result for the influence of Pluto on minor bodies crossing its orbit, the same method of finding Plutino fugitives should be applied to Centaurs and TNOs as selected in this thesis as well as clones of these objects for a larger sample size, which would have been beyond the scope of this work.

As additional result this thesis found that 2 of 158 current Centaurs integrated entered the inner Solar System in a system with Pluto, which are 1.3%. And of 340 TNOs integrated in a system with Pluto 3 were found to enter the inner Solar System, which equals 0.9%. This are numbers rather small compared to previous results, but one has to keep in mind, that the sample of objects was compiled of only Centaurs and trans-Neptunian objects of the current epoch that also cross the orbit of Pluto, which must be regarded as a strong constraint for comparing these results to those of other authors.

After the integration of the 441 Plutinos four of those left the resonance to have encounters with other planets. One of those objects also entered the inner Solar System which equals 25%, but integrated in a system without Pluto. For further investigation it would be interesting to produce clones of those four objects to investigate their dynamical pathways, and to see if the same ratio enters the inner Solar System and to see if the amount of Plutino fugitives is comparable to the method that considers the maximum deflection of objects as criteria for objects being fugitives.

5.2 Outlook into the Future

Space mission, space telescopes and surveys as well as ground based observations were and will be essential in improving the knowledge of our Solar System as well as going beyond to answer question regarding stars and galaxies in the Universe surrounding us.

The long awaited launch of the James Webb Space Telescope (JWST) took place on the 25. December 2021. It was launched on an Ariane 5 rocket at the Arianespace launching site in French Guiana[1]. JWST has an impressive 18 segmented 6.5 m primary mirror with adjustable optics and built-in integrated wavefront sensing, a 21 x 14 meter sunshield as well as a collection of infrared-optimized instruments, high resolution imaging, spectroscopy and coronagraphy. This 10 year science mission is led by NASA (USA's National Aeronautics and Space Administration) in collaboration with ESA (European Space Agency) and CSA (Canadian Space Agency) to explore the origin of planets, stars and galaxies in the Universe at the Earth's second Lagrange point (Kalirai, 2018).

The JWST is the successor of the Hubble-Space Telescope (HST) a space-based telescope for planetary science and astrophysics. Compared to that JWST has better sensibility, spatial resolution and coverage as well as a larger geographic area of exploration. Its equipment makes it fit for answering question about formation and evolution of our planetary system. Due to its high fidelity infrared (IR) imaging and spectroscopy it can explore bodies in the Solar System and its compositional structure too faint or distant to be observed until now. In addition, JWST will observe exoplanetary systems and

[1] `https://webb.nasa.gov/content/about/launch.html`

its physical processes which will provide implications that can be applied to our Solar System. Of great interest of observation are small bodies beyond the orbit of Neptune. These primitive bodies were too faint to be studied in near and mid IR from ground based facilities but retain information about the processes and chemistry of the early stages of the formation of the Solar System. The improved sensibility of JWST makes it possible to characterize the compositional structures of these objects as well as albedo, diameters and thermal properties of these objects of interest. Especially Kuiper-Belt objects (KBOs) or trans-Neptunian objects (TNOs) including four of the dwarf planets (Pluto, Eris, Haumea and Makemake) could give important insights into the formation of planetesimals in the protoplanetary disk and solar nebula. These planetesimals are remnants of the planetary accretion process and were moved at far distances due to the outward migration of Neptune. Today these objects can be categorized into distinct dynamical classes, their properties are regarded as key questions about the formation and evolution of the outer Solar System.

The New Horizons mission completed a fly-by of Pluto in 2015 and brought back data in ultraviolet, in the visible and in the near IR. JWST will be able to observe Pluto and its moons in different parts of the spectrum. Pluto and Charon are bright enough to be resolved with near-IR spectroscopy with NIRspec, its other four moons will be observed with photometry by using NIRCam filter (Norwood et al., 2016). New Horizon was launched on the 19. January 2006 and was continued to examine the Kuiper-Belt region, the Kuiper-Belt objects (KBOs) as well as the Centaurs and performed a close fly-by of the "cold classical" KBO Arrokoth (*2014 MU69*) (Stern et al., 2018b).

New Horizon brought back a lot of important findings of the region beyond Neptune, like for example that TNOs are diverse, that Pluto has an active surface and that Arrokoth is a contact binary. With data provided by the New Horizons mission arised new questions which make it worth to return to Pluto and other TNOs to study the diversity of these objects. Persephone, the Pluto system orbiter and Kuiper-Belt explorer, named after the queen of the underworld in Greek mythology, is a NASA concept mission that wants to answer these questions. The nominal mission is set to 30.7 years, it will launch in 2031 and is prepared to reach Pluto in 2058. Persephone carries 11 scientific instruments and on its way to Pluto it will encounter one large TNO. Potentially this mission can be extended for eight years, including another close fly-by of a TNO. The scientific goals of Persephone are the exploration of the internal structures of Pluto and Charon, how the surfaces of these two objects evolved, as well as how the KBOs evolved and particles and magnetic field environments of the Kuiper-Belt. Of particular interest is the question if Pluto has a subsurface ocean, which would give astrobiological conclusions about the Solar System. Therefore, Persephone will orbit within the Pluto system and encounter other TNOs. This is important because the diversity of TNOs, which are small and faint objects far away, can not sufficiently be observed with ground-based facilities. Persephone should make it possible to contribute to the knowledge of KBOs, Kuiper-Belt binaries as well as the evolution of the Kuiper-Belt on the whole (Howett et al., 2021). Of course, this is only a selection of space missions and observation opportunities that will exist in the future or have existed in the past.

6 Conclusion

The gravitational influence of weak perturbations and close encounters of Pluto makes it possible for objects in its vicinity to change their orbital elements and become Centaurs, Jupiter-family comets or even Near-Earth objects. The results of the numerical integration had shown that the Plutinos have the most frequent encounters with Pluto, as they are also the group of objects most commonly found in its vicinity, because Pluto itself is a member of the Plutinos. In total 42.6% of all Plutinos had at least one close encounter with Pluto, four of these objects left the 2:3 MMR during the numerical integration of 50 Myr. However, only 8.2% of the Centaurs and 11.8% of Trans-Neptunian objects that cross the orbit of Pluto, were found to experience at least one close encounter with the dwarf planet.

The analysis of the descriptive statistics of the results of the close encounters with Pluto showed that the majority of the changes of the semi-major axis in all examined small body groups is only very small and the size does not differ noticeably from each other. In a similar way the distribution of the minimum distance during a close encounter between the small body populations and Pluto was presented, which is in a similar range for all groups. This is not surprising, since all of these objects originate in the same region and show similar size and color distributions. Performing a Pearson analysis between change in semi-major axis and minimum distance showed that there is no strong correlation for the different groups, except for Plutinos that left resonance during numerical integration. According to the Öpik theory of close encounters the change in semi-major axis is inverse proportional to minimal distance and velocity squared, the latter value is missing in this analysis, which can therefore be interpreted as an approximate evaluation.

The main results of this thesis was the investigation of the influence of Pluto on the Plutinos. Therefore the maximum deflection of each integrated Plutino was determined. If the maximum deflection was larger than the critical value of $3\sigma_a = 0.571\,\text{au}$ it was considered as a fugitive. The comparison of fugitive Plutinos in a system with and without Pluto showed that Pluto has only a moderate influence on decreasing the Plutino population of about 3%. 31.1% of Plutinos can be considered as fugitives in a system with Pluto, whereas 28.1% are defined as fugitive in a system without Pluto. The values of the maximum deflection of the semi-major axis lie in a similar range for analysis with and without Pluto. To proof this result it should be considered to apply this method to the population of Centaurs and TNOs as considered in this thesis.

When comparing the results of this work, namely that Pluto has only a moderate effect on increasing the number of Plutinos leaving their 2:3 MMR, with studies by other authors previously made, the results are consistent. Tiscareno and Malhotra (2009) found that Pluto's influence results in a $\sim 4\%$ decrease of in Plutino population that survive the integration time. But they also found a that only 27% of the Plutinos survive the projected integration time of 4 Gyr in a system with Pluto, and 28% in a system without Pluto, which is much more than found in this work. The reason could be that due to different methodical setup and choices of how to define a fugitive these values differ so much from each other. For example while Tiscareno and Malhotra (2009) used the four giant planets in addition to Pluto for integration of 1 Gyr of fictitious resonant particles, this thesis used all planets including Pluto and minor bodies of the current epoch with an integration time of 500 Myr. Moreover, here a resonant object was considered as a fugitive if its maximum defection reached a critical value while Tiscareno and Malhotra (2009) defined a particle leaving the resonant zone when its value of semi-major axis is ± 0.7 au from their central resonant value.

An additional result was the examination of a change in the trajectory of the minor bodies due to a close encounter with Pluto and how many of those enter the inner Solar System. Of all Plutinos that were integrated four left the 2:3 MMR with Neptune in a system with Pluto, whereas only two left it in a system without Pluto. One Plutino was found that had a major change in semi-major axis due to Pluto, and engaged in a chaotic orbit. Moreover, it was discovered that one Plutino integrated in a system without Pluto reached the terrestrial planet region, with $q = 2.59$ au at about 49.8 Myr. For more significant details, one should consider to produce clones of these Plutinos and perform numerical integrations again with Pluto and without Pluto and investigate the difference of objects leaving the resonance as well as bodies entering the inner Solar System with a larger and more specified sample of Plutinos that also considers current estimations of number of populations.

Interestingly more Centaurs were found that enter the inner Solar System in a system integrated without Pluto. Five Centaurs evolve to a perihelion distance smaller than 5 au without Pluto, whereas only two reach the terrestrial planet region in a system with Pluto. Further investigations could confirm that Pluto could have a contrary effect on Centaurs that cross its orbit, by deflecting them into the outer regions into the Solar System. Regarding the group of other trans-Neptunian objects, a similar amount of objects was found that entered the inner planetary region in a system with and without Pluto. Also the orbital evolution of TNOs in a system with(out) Pluto does not differ much. It seems reasonable that Pluto has the same moderate effect on TNOs than on the Plutinos, but since less TNOs arrive at its vicinity this effect should be proven with an improved and larger sample of TNOs.

Comparing these results with studies previously made by other authors it can be seen that the number of objects entering the inner planetary region in this work is very small compared to others. This could be due to different choices in sample sizes and distribution, one has to keep in mind, that in this theses only TNOs and Centaurs that cross the orbit of Pluto were considered.

Summing up, it can be said that Pluto has only a minor influence on most objects that cross its orbit, but some cases are found were its effect is significant, specifically on individual Plutinos. Still this thesis produced some interesting results, that can be further investigated and compared to studies by other authors, like the effect that Pluto has on the Centaur population or to determine how many Plutinos will survive from now on. Since all calculations here were made with currently observed objects estimations also about population sizes of the past could be investigated further.

In the future these theoretical models could be further improved by new knowledge and insights coming from new planned space missions and telescope. With the launch of the James Webb Space Telescope (JWST) it will be possible to observe objects in the trans-Neptunian region that were too faint and to far away until now. Also Persephone, a space mission led by NASA will bring back new information about formation and evolution of Pluto and Charon, which represent members of the TN-region, and are therefore important for describing the evolution of other bodies in the Solar System.

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Acronyms

HST Hubble Space Telescope. 10

HTO Halley-Type object. 2

JFC Jupiter-family comet. 2, 22

JWST James Webb Space Telescope. 3, 57

MMR Mean-Motion resonance. 1, 6, 9

NEO Near-Earth object. 2

R3BP Restricted Three Body Problem. 28

SR Secular Resonance. 9

TNO trans-Neptunian object. 10

Glossary

au Astronomical Unit, the distance from Sun to Earth defines the unit 1 astronomical unit (au) which equals $149.6 \cdot 10^6$ km. 1

G Gravitational Constant, the value of G is $(6.6743 \pm 0.00015) \times 10^{11}\, m^3 kg^1 s^2$. 7