



UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
CAMPUS DE GUARATINGUETÁ

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Dynamical evolution, transport and detection of minor bodies in the Solar System

Guaratinguetá / Brazil

2023

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Dynamical evolution, transport and detection of minor bodies in the Solar System

Doctoral Thesis presented to the Graduate Program in Physics and Astronomy of the Sao Paulo State University "Júlio de Mesquita Filho" as a partial requirement to obtain the degree of Doctor in Physics and Astronomy

Universidade Estadual Paulista "Júlio de Mesquita Filho"

Graduate Program in Physics and Astronomy

Supervisor: Prof Dr Othon Winter

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Guaratinguetá / Brazil

2023

M538d Mendes, Luana Liberato
Dynamical evolution, transport and detection of minor
bodies in the solar system / Luana Liberato Mendes -
Guaratinguetá, 2023.
109 f : il.
Bibliografia: f. 101-109

Tese (Doutorado-Física) – Universidade Estadual Paulista,
Faculdade de Engenharia e Ciências de Guaratinguetá, 2023.

Orientador: Prof. Dr. Othon Winter
Coorientador: Dr. Paolo Tanga

1. Astrometria. 2. Asteróides. 3. Sistema solar. I. Título.

CDU 521.9(043)

Luciana Máximo

Bibliotecária/CRB-8/3595

unesp



**UNIVERSIDADE ESTADUAL PAULISTA
CAMPUS DE GUARATINGUETÁ**

LUANA LIBERATO MENDES

**ESTA TESE FOI JULGADA ADEQUADA PARA A OBTENÇÃO DO TÍTULO DE
“DOUTOR EM FÍSICA”**

**PROGRAMA: FÍSICA
CURSO: DOUTORADO**

APROVADA EM SUA FORMA FINAL PELO PROGRAMA DE PÓS-GRADUAÇÃO

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Outubro de 2023

I dedicate this thesis to all my loved ones.
Those that are still here and those that now live in memories.

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Acknowledgements

First I would like to thank the members of the board and the substitute members for accepting to participate and taking the time to evaluate my work and give valuable suggestions.

A special thanks to my supervisor, Othon Winter, for teaching, supervising and supporting me for the past 10 years. You always encouraged me to follow the path I wanted and gave me the autonomy, help and guidance I needed to do it. Because of you, I will be able to continue to pursue my goals. For all of that, and much more, my most sincere thank you!

Next, I would like to give big thanks to Paolo Tanga for supervising me during my stay in Nice, for receiving me so kindly, for all the guidance and for helping me through my journey in a new research field. But more importantly, thank you for believing in me, opening so many doors for me and giving me the opportunity to continue my career doing what I love. Grazie!

My sincere thanks to my collaborators Rosana Araujo, David Mary, Benoit Carry, Kate Minker, Federica Spoto, Valerio Carruba, Rafael Ribeiro, Gustavo Benedetti-Rossi, GDOP, Gaia Moons and Rio Group teams for their contributions, and to all of my professors and colleagues who somehow helped me get where I am now.

Thanks to all my friends from my post-graduation program and a special thanks to my dear friends who have been with me literally since the first day of undergraduate, Tiago Francisco, Victor Lattari and Gustavo Madeira. You all made my days happier and lighter. Thank you for all the partnership, the jokes, the laughs, the truco and the pool matches.

A special thanks to all my amazing friends from the Observatoire de la Côte d'Azur, especially my fellow Sun seals Marjorie Galinier, Fabiola Gerosa and Philippine Griveaud. You all received me with open arms and made my first stay in Nice extraordinary.

I also thank my family for their love, support and for giving me the privilege of pursuing the career I chose. My parents, Ruth and Gilberto, my sister Katia and my niece Giovanna. Thank you for always believing in me and for giving me the strength to keep going. Without you, I would be nothing.

To my babies Doguinho, who is now in heaven, and Thor. Thanks for keeping me company through all of my days and nights of work and for your unconditional love.

And finally, thanks to me for working hard and for never giving up.

This study was financially supported by:

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001

CAPES-PRINT Process 88887.570251/2020-00

Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - Process 305210/2018-1

FAPESP Process 2016/24561-0

French Programme National de Planetologie

BQR program of Observatoire de la Côte d’Azur

Project GaiaMoons of the Agence Nationale de Recherche (France), grant ANR-22-CE49-0002

Resources supplied by the Center for Scientific Computing (NCC/GridUNESP) of the São Paulo State University (UNESP)

This work presents results from the European Space Agency (ESA) space mission Gaia. Gaia data are being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement (MLA). The Gaia mission website is <https://www.cosmos.esa.int/gaia>. The Gaia archive website is <https://archives.esac.esa.int/gaia>.

"Il faut bien que je supporte deux ou trois chenilles si je veux connaître les papillons."

Le petit prince - Antoine de Saint-Exupéry

Abstract

The Near-Earth Objects (NEOs) population is sustained by bodies coming from the main asteroid belt and outer regions of the Solar System. In this study, we revisit the dynamic evolution of the known NEO population using a sample of 985 large objects with diameters $> 1\text{km}$. N-body gravitational simulations for 100 million years track their transferences between regions, revealing their most common routes and fates. Objects transferred to orbits very close to the Sun are eliminated due to the thermal disruption effect, which is the most efficient NEO removal mechanism affecting 70% of the objects. Over half of the bodies are transferred to the Jupiter Family Comets (JFC) region, and an even larger percentage exits the Solar System through it. Frequent exchanges occur between NEO and Main Asteroid Belt (MAB) regions, with nearly 30% of the studied sample moving to MAB, but less than 1% remaining in it. Approximately 14% of the studied NEOs survive or collide with one of the terrestrial planets, while 10% can reach the Centaurs (CEN) region and remain inside of it for a significant time. Regarding the NEOs' inclination, observations reveal significant deviations from near-planar orbits. To address this, we study their evolution and the impact of the orbital inclination in the NEOs' lifetimes. We find that NEOs' environment encourages an increase in orbital inclination, favouring long-lived NEOs with an intermediate orbital inclination of approximately 20° to 60° . Additionally, we focus on the study of the objects that collided with the planets and find that the NEOs with intermediate orbital inclinations represent a constant risk of collisions for their regular number of impacts with the Earth and Venus, leading to a frequency of one impact of a km-size object each $\sim 0.22\text{Myrs}$ and $\sim 0.13\text{Myrs}$, respectively. Furthermore, approximately 2.5% of the studied NEO population eventually became Vatiras (objects between Mercury and Venus), which indicates that a population of inner-Venus km-sized objects should exist and they might represent a significant risk of collisions with our planet. Turning attention to the binary asteroids, studies of such objects provide valuable insights into the collisional and dynamical evolution of minor planets. Therefore, we perform a dedicated period detection method based on astrometry using the Gaia DR3 data set, where we aim to reduce observational bias and discover new binary systems. A series of filterings and validations yielded a list of 67 binary candidates, awaiting confirmation through other observation techniques. These findings can contribute to a comprehensive understanding of minor body dynamics and physical properties, with implications for different topics in Solar System evolution studies.

Keywords: NEO. Dynamical evolution. Numerical simulations. Minor bodies. Gaia mission. Binary asteroids. Astrometry.

Resumo

A população de Objetos Próximos à Terra (NEOs) é sustentada por corpos provenientes do cinturão principal de asteróides e de regiões externas do Sistema Solar. Neste estudo, revisitamos a evolução dinâmica da população conhecida de NEO usando uma amostra de 985 objetos grandes com diâmetros $> 1\text{km}$. Simulações gravitacionais de N corpos durante 100 milhões de anos rastreiam suas transferências entre regiões, revelando suas rotas e destinos mais comuns. Objetos transferidos para órbitas muito próximas do Sol são eliminados devido ao efeito de ruptura térmica, que é o mecanismo de remoção de NEO mais eficiente, afetando 70% dos objetos. Mais de metade dos corpos são transferidos para a região dos Cometas da Família de Júpiter (JFC), e uma percentagem ainda maior sai do Sistema Solar através dela. Trocas frequentes ocorrem entre as regiões NEO e do Cinturão Principal de Asteróides (MAB), com quase 30% da amostra estudada movendo-se para a região MAB, mas menos de 1% permanecendo nela. Aproximadamente 14% dos NEOs estudados sobrevivem ou colidem com um dos planetas terrestres, enquanto 10% podem alcançar a região dos Centauros (CEN) e permanecer dentro dela por um tempo significativo. Em relação à inclinação dos NEOs, as observações revelam desvios significativos das órbitas quase planares. Para entender isso, estudamos a sua evolução e o impacto da inclinação orbital na vida dos NEOs. Descobrimos que o ambiente dos NEOs incentiva um aumento na inclinação orbital, favorecendo uma vida longa aos NEOs com inclinação orbital intermediária de aproximadamente 20° a 60° . Adicionalmente, nos concentramos no estudo dos objetos que colidiram com os planetas e descobrimos que os NEOs com inclinações orbitais intermediárias representam um risco constante de colisões pelo seu número regular de impactos com a Terra e Vênus, levando a uma frequência de um impacto de um objeto de tamanho km cada $\sim 0.22\text{Myrs}$ e $\sim 0.13\text{Myrs}$, respectivamente. Além disso, aproximadamente 2.5% da população NEO estudada eventualmente se tornou Vatira (objetos entre Mercúrio e Vênus), o que indica que deveria existir uma população de objetos do tamanho de quilômetros interior a Vênus e que poderiam representar um risco significativo de colisões com nosso planeta. Voltando a atenção para os asteróides binários, os estudos de tais objetos fornecem informações valiosas sobre a evolução colisional e dinâmica de corpos menores. Portanto, realizamos um método de detecção de período baseado em astrometria usando o conjunto de dados Gaia DR3, onde pretendemos reduzir o viés observacional e descobrir novos sistemas binários. Uma série de filtragens e validações rendeu uma lista de 67 candidatos binários, aguardando confirmação por meio de outras técnicas de observação. Estas descobertas podem contribuir para uma compreensão mais abrangente da dinâmica e das propriedades físicas dos corpos pequenos, com implicações para diferentes tópicos nos estudos de evolução do Sistema Solar.

Palavras-chave: NEO. Evolução dinâmica. Simulação numérica. Pequenos corpos. Missão Gaia. Asteróides binários. Astrometria.

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List of abbreviations and acronyms

a	Orbital Semi-major Axis
au	Astronomical Units
CEN	Centaur
DR2	Data Release 2
DR3	Data Release 3
e	Orbital Eccentricity
EEB	Escaping Ejecta Binaries
i	Orbital Inclination
JFC	Jupiter-family Comet
MAB	Main Asteroid Belt
mas	Milliarcseconds
MMR	Mean Motion Resonance
Myrs	Million years
NEO	Near-Earth Object
q	perihelion distance
TNO	Trans-Neptunian Object

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1 Introduction

The Solar System, an intricate and vast cosmic realm, comprises a diverse collection of celestial bodies ranging from massive planets to minor bodies like asteroids, comets, meteoroids and dust grains. These minor bodies, remnants of the early stages of the Solar System’s formation, play a vital role in understanding its evolution and the processes that have shaped its current dynamical and physical state. Among the minor bodies, asteroids hold a prominent place due to their abundance and diverse orbits.

Classifying minor bodies based on their orbital characteristics provides crucial insights into their origins and evolutionary pathways. The Solar System presents a fascinating array of possibilities, from meter-sized asteroids residing inside Venus’ orbit to dwarf planets positioned beyond Neptune. Notable among the classes are the Trans-Neptunian Objects (TNOs) beyond Neptune, the Centaurs located between the orbits of Jupiter and Neptune, the asteroids in the Main Belt between Mars and Jupiter, and the Near-Earth Objects (NEOs) situated within the region of terrestrial planets.

NEOs, in particular, have garnered significant attention due to their close proximity to Earth and potential impact hazards (Delbò et al., 2007; Devyatkin et al., 2022; Huebner et al., 2009). The concept of NEOs dates back to the late 19th century when astronomers first recognised the existence of asteroids and comets with orbits that closely intersected Earth’s path. The first NEO to be discovered was the asteroid 433 Eros in 1898 by astronomer Gustav Witt (Berberich, 1898). However, it wasn’t until the latter half of the 20th century that the systematic study of NEOs gained momentum. Over the years, the efforts to identify and catalogue NEOs increased exponentially, thanks to advanced telescopes and computing technologies.

NEOs possess several defining features, including their proximity to Earth, exhibiting orbits that come close to or even cross our planet’s orbit. Their orbits can vary significantly in shape and inclination, ranging from nearly circular and planar to highly eccentric and inclined paths. Additionally, NEOs encompass a wide size range, from small meter-sized objects to large asteroids with diameters of several hundreds of kilometers¹ as shown in Figure 1.

Comprising asteroids, comets, and meteoroids, NEOs pose a crucial challenge in planetary defence and offer valuable insights into the dynamic processes of the Solar System. Research over the past few decades has revealed that the transport of asteroids from outer regions to the vicinity of terrestrial planets is a common occurrence (Gladman et al., 1997, 2000; Michel et al., 2000; Bottke et al., 2002; Raymond and Nesvorny, 2021).

There are several classes of objects believed to contribute to the maintenance of the NEO population. The TNOs (Levison and Duncan, 1997; Tiscareno and Malhotra, 2003; Araujo et al., 2018a) and Centaurs (Horner et al., 2004; Wood and Horner, 2015) have a significant contribution to the NEO population. However, the majority of objects are believed to originate mainly in the main belt and a significant part in the Jupiter-family

¹ <https://neo.ssa.esa.int/discovery-statistics>

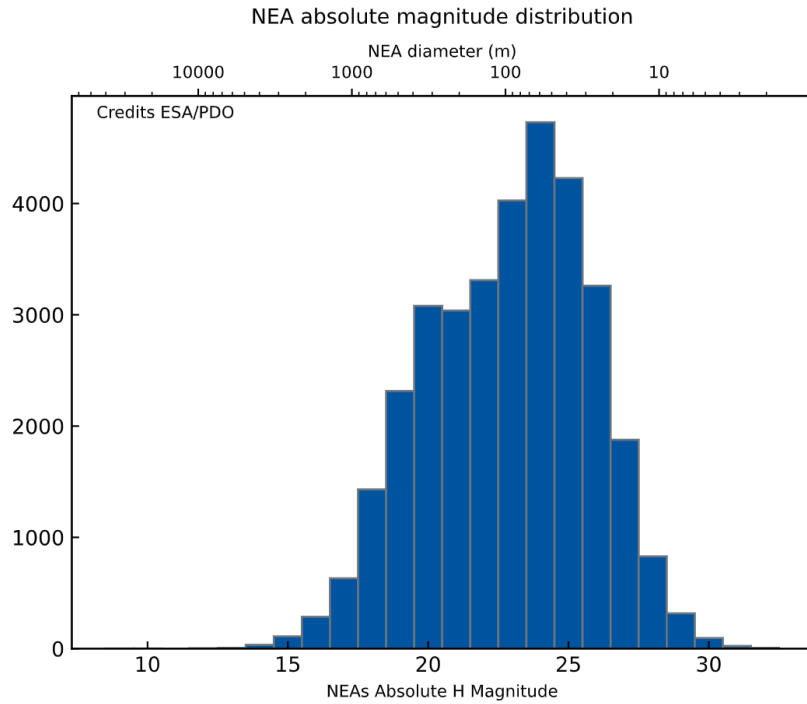


Figure 1 – Distribution of the number of currently known NEOs per absolute H magnitude and estimated diameter. Source: NEOCC/ESA

comets (Morbidei et al., 2002; O’Brien and Greenberg, 2005; Greenstreet et al., 2012b; Kaplan et al., 2016; Granvik et al., 2018).

The asteroids are believed to be the remnant from the formation of the planets in the Solar System and therefore should have kept about the same orbital characteristics and distribution, which explains why most of them present orbits with low inclinations and small eccentricities (Morbidei et al., 2015; Deienno et al., 2016). However, as we observe today, a part of these objects evolved into eccentric and inclined orbits due to the encounters with the planets and the effects of resonances (Petit et al., 2002; Terai and Itoh, 2011; Morbidei et al., 2015).

The population of objects in the main belt is mainly composed of asteroids with orbits with relatively low eccentricity ($e < 0.2$) and low inclination ($i < 20^\circ$) (Terai and Itoh, 2011; IAU-MPC, 2023), as can be observed in Figure 2. The main asteroid belt encompasses a region majorly affected by mean motion resonances (MMR) (Gallardo, 2006). The distribution of the asteroids in the main belt is mainly influenced by their interactions with Jupiter, leading to clusters at resonances such as 3:2, 4:3, and 1:1, and gaps at resonances like 2:1, 3:1, 5:2, and 7:3, known as the Kirkwood Gaps (Moons, 1996; Nesvorný and Morbidei, 1998; Tsiganis et al., 2002; Todorović, 2017). These resonances can produce chaotic behaviour that increases the orbital eccentricities and/or inclination of asteroids, causing significant deviations from their initial orbits, and potential encounters with Mars’ orbit (Wisdom, 1982).

Previous works show that NEOs are objects ejected from the main belt through complex dynamical processes involving mean motion and secular resonances. The chaos

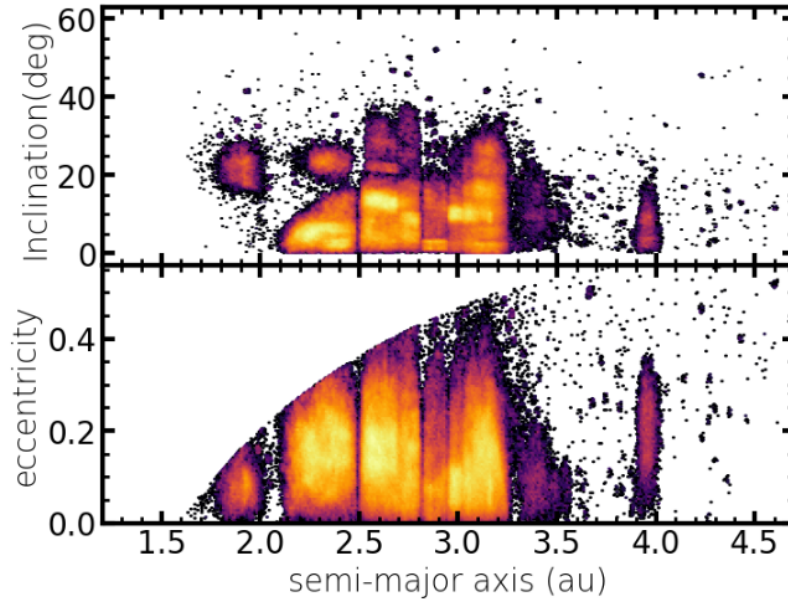


Figure 2 – Distribution of (a,i) in the top plot and (a,e) on the bottom plot for $\sim 1.3 \times 10^6$ asteroids in the main belt with orbital data from the Minor Planet Center (IAU-MPC, 2023). Brighter regions represent a higher density of objects.

due to the overlap of MMR affects the bodies in the vicinity, leading them to an erratic and chaotic dynamical evolution that delivers these objects to the NEO region (Wisdom, 1982; Dermott and Murray, 1983; Morbidelli, 1999; Morbidelli and Nesvorný, 1999; Milani et al., 2014; Dermott et al., 2021). Secular resonances, including ν_5 , ν_6 , and ν_{16} , also rule the long-term evolution of small bodies in the asteroid belt (Morbidelli and Moons, 1993; Froeschlé et al., 1997; Michel and Froeschlé, 1997; Ji et al., 2006). Additionally, the Kozai-Lidov resonance emerges as a significant driver of asteroid evolution in the near-Earth region (de la Fuente Marcos and De la Fuente Marcos, 2016; Kozai, 1962).

Furthermore, the Yarkovsky effect is a phenomenon that plays a crucial role in the evolution of small objects. It is a non-gravitational force that arises due to the asymmetric absorption and re-emission of solar radiation by an asteroid. This process leads to a slight but consistent change in the asteroid's orbit over time (Rubincam, 1982). The magnitude of the Yarkovsky effect is mainly dependent on the physical properties of the object, such as the diameter, rotation period, albedo, and solar radiance at the object's surface, among other surface parameters (Farinella and Vokrouhlický, 1999; Bottke et al., 2000). For instance, for an object of 1Km in the main belt, the Yarkovsky drift is estimated to be at the order of 10^{-4} au/Myrs (Bottke Jr et al., 2002; Delbo' et al., 2007), which makes it the most important effect causing changes in the orbits of small main-belt objects.

Due to the slow but constant drift in the semi-major axis, the Yarkovsky effect can drag objects from stable orbits in the main belt into chaotic resonance regions called escape routes, which can deliver them to near-Earth orbits (Bottke et al., 2002; Bottke Jr et al., 2006; Morbidelli and Vokrouhlický, 2003). Objects travelling at higher speeds due to the Yarkovsky effect are prone to crossing these small resonances while slower-moving objects can become trapped (Bottke et al., 2002). However, once the large objects (diameter $>$

1 km) cross the pericenter of 1.3 au and become a NEO, the Yarkovsky effect becomes negligible in comparison with the gravitational perturbations from the terrestrial planets, which is 5 orders of magnitude larger than the Yarkovsky thermal force (Granvik et al., 2018).

Additionally, the objects under the perturbation of the Yarkovsky effect do not have the location of their escape routes significantly changed, only the timescales in which the escape takes place (Granvik et al., 2017). Furthermore, objects that escaped from the main belt do not present significant differences in the orbital distribution when they are under the Yarkovsky effect influence (Granvik et al., 2018). Therefore, even though the Yarkovsky effect is one of the most important perturbations to the asteroids' dynamics, it can be neglected in some studies without major loss in the statistical results.

The estimated dynamical lifetime of the NEO population is 10 Million years (Gladman et al., 2000), which supports the assumption that this population is in a steady state and is constantly resupplied by objects from outer regions (Bottke Jr et al., 2002; Granvik et al., 2016, 2018). The distribution of orbital inclination of the NEO population shows a much higher rate of high-inclination objects in the terrestrial planets region than in the main belt, as shown in Figure 3. However, only a fraction of the high-inclination NEOs came from high-inclination asteroids in the main belt (Zain et al., 2020). In fact, it is estimated that only about 2% of the NEO population in the steady state evolves to retrograde objects (Greenstreet et al., 2012a; Granvik et al., 2018). Furthermore, there are several works showing that, after arriving from the main belt, the NEOs can still move to different parts of the Solar System and have different sets of fates (Gladman et al., 2000; Granvik et al., 2018; Siregar, 2010).

However, several interesting questions remain unanswered, prompting a reevaluation of the problem of the large known NEO dynamical evolution. How do large NEOs evolve once they enter the region of terrestrial planets? Do they follow preferential pathways, and how does this evolution impact their lifetimes and final fates? What are the processes that lead to the increase in inclination observed in the large known NEO population? What role does the inclination play in the lifetime of the objects in the NEO region? Addressing these questions is crucial for understanding the long-term stability and dynamics of the large known NEO population.

Another intriguing aspect of minor bodies is the presence of binary asteroids, systems in which two bodies orbit their common centre of mass. The first asteroid satellite discovery was made by the NASA Galileo spacecraft. Images of the asteroid (243) Ida, taken during a fly-by in August 1993, showed a small moon orbiting the asteroid which was then named Dactyl (Chapman et al., 1995). Since then, almost 500 minor bodies have been known to have at least one companion satellite².

Binary asteroids offer unique opportunities to explore fundamental processes such as planetary body formation, collision dynamics, and gravitational interactions (Durda et al., 2004; Pravec and Harris, 2007; Scheeres, 2007; Pravec et al., 2010).

Figure 4 shows the distribution of diameter versus rotation period of the primary

² <https://www.johnstonsarchive.net/astro/asteroidmoons.html> and references therein

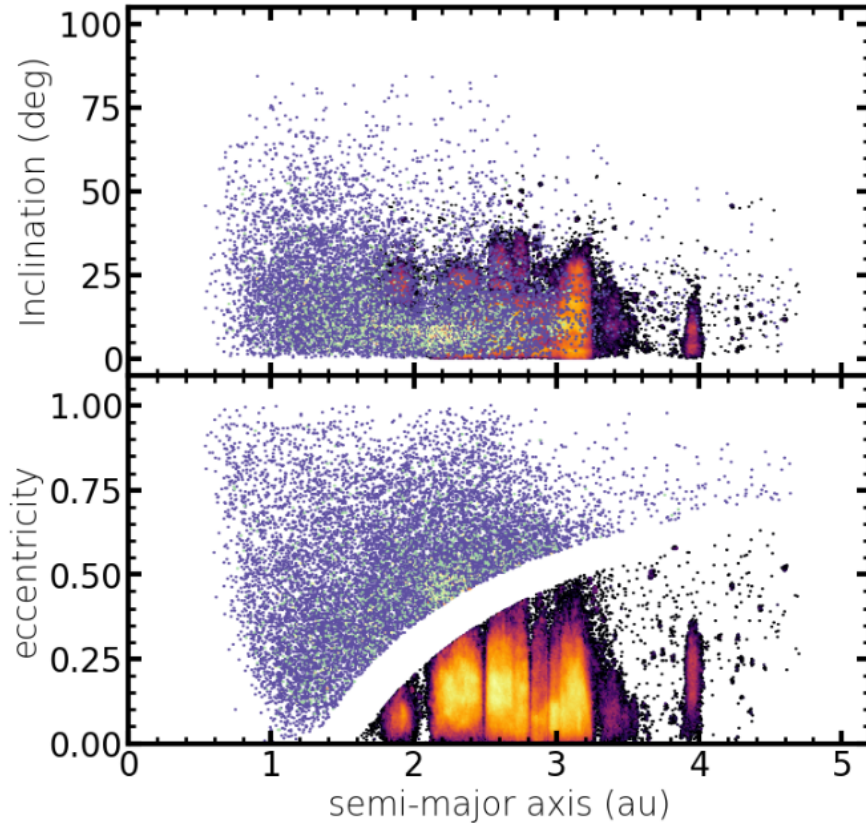


Figure 3 – Distribution of (a,i) in the top plot and (a,e) on the bottom plot for the main belt asteroids and NEO populations with orbital data from the Minor Planet Center (IAU-MPC, 2023). Brighter regions represent a higher density of objects. The purple-green dots represent the NEOs and the black-yellow dots represent the main-belt asteroids.

for the different detection techniques. The rectangles represent the binary asteroid groups (Pravec and Harris, 2007; Pravec et al., 2010). Group A is composed of fast-rotating and small primary asteroids. Group B contains systems with small primaries but binaries with similar sizes ($D_2/D_1 \sim 1$) that rotate slower as the primary diameter increases. Group L is for the large and fast-rotating objects.

However, due to limitations in observations, some types of binary asteroids are preferentially detected. The widely separated or bright objects are favoured in the case of direct imaging, while compact systems are more easily detected using the photometric light-curve technique (Merline et al., 2002; Richardson and Walsh, 2006) and the radar observations are strongly limited and can only detect with more confidence binary asteroids close to the Earth (Ostro et al., 2002). Additionally, stellar occultations and space probes were already used to detect such objects (Belton and Carlson, 1994; Gault et al., 2022), but they represent a small contribution to the statistics of the population.

In general, the small binary asteroids (diameter $\lesssim 20$ km) are most likely formed by some process of mass shedding and in-orbit material re-accumulation (Pravec and Harris, 2007; Walsh et al., 2008).

Notice that the intermediate size range (20-100 km) is underrepresented, with only

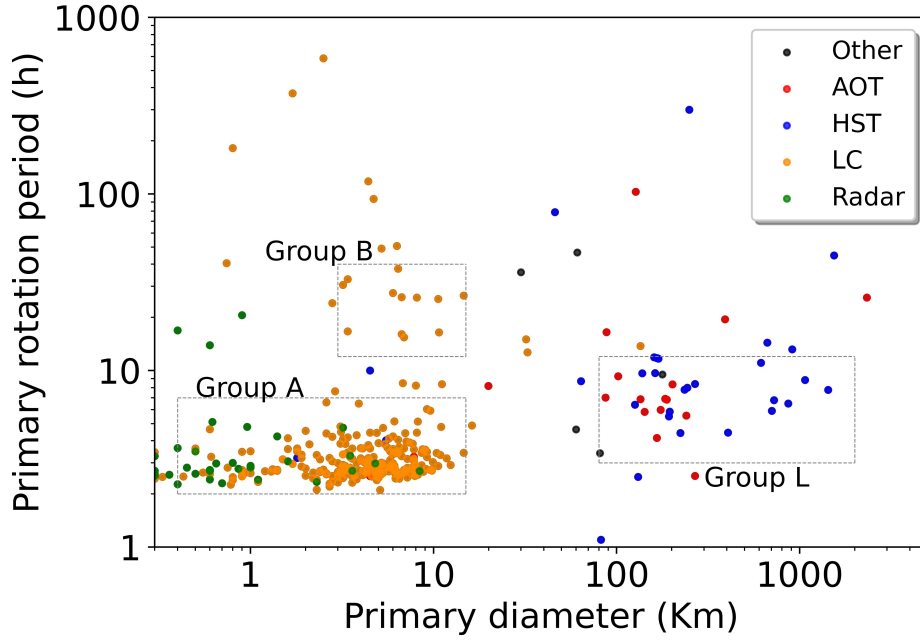


Figure 4 – Distribution of primary diameter versus rotation period of the primary for the known binary asteroid population. The colours represent the different detection techniques: Radar, Light Curve (LC), direct imaging with telescopes using adaptative optics (AOT), direct imaging with Hubble space telescope (HST), and other less common techniques such as stellar occultations or imaging with space probes. The three different groups are indicated (A, B and L) depending on the object’s relative sizes and rotational period (see text).

~5% of the total known population. Several models and observations support that some of these objects were formed from the disruption of a parent body (Descamps et al., 2009; Marchis et al., 2011). A similar mechanism is believed to form Escaping Ejecta Binaries (EEBs) (Doressoundiram et al., 1997; Durda et al., 2004) that should be the resulting fragments from a collision at low relative velocity.

However, there are still some knowledge gaps about the origin and formation of binary asteroid systems and their dynamical evolution. To understand better these objects, we need a statistically significant and diverse sample of binary systems, which is currently limited. Even though the detection of binary asteroids using astrometric data cannot solve all the problems, deal with the bias and fill all the gaps, it can assist in the detection of objects in spaces unreachable for other observation techniques (Pravec and Scheirich, 2012).

Astrometry plays a crucial role in understanding the structure and dynamics of bodies in the Solar System, and in the universe as a whole. It focuses on the precise measurement of the positions and motions of celestial objects in the sky to determine their distances, proper motions, and parallaxes. The astrometric data of asteroids is essential for predicting their future positions and assessing potential collision risks with Earth, for example.

The Gaia mission is a European Space Agency (ESA) project launched in 2013 with

the primary goal of performing precise astrometric measurements for all sources of light in space with magnitude $G \gtrsim 20$. The Gaia DR3 provided high-precision astrometric data for more than 150,000 asteroids, which allows us to search for companions, as predicted during the development of the mission (Mignard et al., 2007; Pravec and Scheirich, 2012).

Detection of an astrometric signature due to an asteroid companion was already found in some cases (Tanga et al., 2022; Ortiz et al., 2011). However, in those studies, the presence of a satellite had already been previously confirmed using other detection techniques. Fortunately, in Tanga et al. (2022) we showed evidence that the ultra-high astrometric accuracy provided in Gaia DR3 is high enough to allow the detection of the astrometric signal generated by an asteroid companion, using asteroid (4337) Arecibo as an example. Therefore, in the work presented in this thesis, we performed a blind search for astrometric binaries in the Gaia Data Release 3 (DR3) asteroids' astrometric data.

This multifaceted research effort aims to increase the understanding of the Solar System's minor bodies, their physical properties and dynamical evolution. The insights gained from this research have broad implications, not only for planetary protection strategies but also for improving the understanding of celestial mechanics, planetary formation, space exploration and the history of the Solar System.

My thesis explores the orbital evolution and detection of different classes of minor bodies in the Solar System. From the study of the orbital dynamic evolution of NEOs to the development of a method for astrometric detection of binary asteroids, I gather a set of studies that enclose an exciting set of results. I present research papers, in different stages of progress, in which the projects were developed during my doctorate. The chapters approach independent topics from each other.

This work is structured as follows:

- In Chapter 3 I present a study of the dynamical evolution of the known large NEOs and the article where we study the evolution of the orbital inclination of the same population of known large NEOs. Furthermore, I make some general discussions about the papers presented and supplementary results not included in any of the works sent for publication. I then draw conclusions and comment on the future steps I plan to work on.
- In Chapter 4 I briefly contextualise the work on astrometric detection of binary asteroids using Gaia DR3 data. Then I present the paper in submission on the topic and make some final comments on this work and the future steps.
- Finally, Chapter 5 presents the main conclusion of the works presented and the key takeaways of this thesis.

2 Introdução

O Sistema Solar, um reino cósmico vasto e complexo, compreende uma coleção diversificada de corpos celestes que vão desde planetas massivos até corpos menores, como asteróides, cometas e meteoróides. Estes corpos menores, remanescentes das fases iniciais da formação do Sistema Solar, desempenham um papel vital na compreensão da evolução e dos processos que moldaram o estado atual do Sistema. Entre os corpos menores, os asteróides ocupam um lugar de destaque devido à sua abundância e variedade de órbitas.

A classificação de pequenos corpos com base em suas características orbitais fornece informações cruciais sobre suas origens e caminhos evolutivos. O Sistema Solar apresenta um fascinante conjunto de possibilidades, desde asteróides de alguns metros que residem dentro da órbita de Vênus até planetas anões posicionados além de Netuno. Notáveis entre as classes são os Objetos Transnetunianos (TNOs) além de Netuno, os Centauros localizados entre as órbitas de Júpiter e Netuno, os asteróides no Cinturão Principal entre Marte e Júpiter, e os Objetos Próximos da Terra (NEOs) situados na região dos planetas terrestres.

Os NEOs, em particular, têm atraído atenção significativa devido à sua proximidade com a Terra e aos riscos potenciais de impacto com o nosso planeta (Delbò et al., 2007; Devyatkin et al., 2022; Huebner et al., 2009).

O conceito de NEOs remonta ao final do século XIX, quando os astrônomos reconheceram pela primeira vez a existência de asteróides e cometas com órbitas que cruzavam o caminho da Terra. O primeiro NEO a ser descoberto foi o asteróide (433) Eros em 1898 pelo astrônomo Gustav Witt (Berberich, 1898). No entanto, foi só na segunda metade do século XX que o estudo sistemático dos NEOs ganhou força. Ao longo dos anos, os esforços para identificar e catalogar NEOs aumentaram exponencialmente, graças a telescópios e tecnologias de computação avançados.

Os NEOs possuem várias características específicas, incluindo a sua proximidade com a Terra, exibindo órbitas que se aproximam ou até cruzam a órbita do nosso planeta. Suas características orbitais podem variar significativamente, variando de órbitas quase circulares e planas a órbitas altamente excêntricas e inclinadas. Além disso, os NEOs abrangem uma ampla gama de tamanhos, desde pequenos objetos do tamanho de um metro até grandes asteróides com diâmetros de várias centenas de quilômetros ¹ como mostrado na Figura 1 ².

Incluindo asteróides, cometas e meteoróides, os NEOs representam um desafio crucial na defesa planetária e oferecem informações valiosas sobre os processos dinâmicos do Sistema Solar. Pesquisas nas últimas décadas revelaram que o transporte de asteróides de regiões externas para a vizinhança de planetas terrestres é uma ocorrência comum (Gladman et al., 1997, 2000; Michel et al., 2000; Bottke et al., 2002; Raymond and Nesvorny,

¹ <https://neo.ssa.esa.int/discovery-statistics>

² Legenda Figura 1: Distribuição do número de NEOs atualmente conhecidos por magnitude absoluta H e diâmetro estimado. Fonte: NEOCC/ESA

2021).

Existem várias classes de objetos que se acredita contribuírem para a manutenção da população NEO. Os TNOs (Levison and Duncan, 1997; Tiscareno and Malhotra, 2003; Araujo et al., 2018a) e Centauros (Horner et al., 2004; Wood and Horner, 2015) têm uma contribuição significativa para a população NEO. No entanto, acredita-se que a maioria dos objetos se origina principalmente no cinturão principal e uma parte significativa nos cometas da família de Júpiter (Morbideilli et al., 2002; O'Brien and Greenberg, 2005; Greenstreet et al., 2012b; Kaplan et al., 2016; Granvik et al., 2018).

Acredita-se que os asteróides sejam remanescentes da formação dos planetas do Sistema Solar e portanto deveriam ter mantido aproximadamente as mesmas características e distribuição orbital, o que explica porque a maioria deles apresenta órbitas com baixas inclinações e pequenas excentricidades (Morbideilli et al., 2015; Deienno et al., 2016). Porém, como observamos hoje, uma parte desses objetos evoluiu para órbitas excêntricas e inclinadas devido aos encontros com os planetas e aos efeitos das ressonâncias (Petit et al., 2002; Terai and Itoh, 2011; Morbideilli et al., 2015), conforme pode ser observado na Figura 2³.

A população de objetos no cinturão principal é composta principalmente por asteróides com órbitas com excentricidade relativamente baixa ($e < 0,2$) e baixa inclinação ($i < 20^\circ$) (Terai and Itoh, 2011; IAU-MPC, 2023). O cinturão principal de asteróides abrange uma região principalmente afetada por ressonâncias de movimento médio (MMR) (Gallardo, 2006). A distribuição dos asteróides no cinturão principal é influenciada principalmente por suas interações com Júpiter, levando a aglomerados em ressonâncias como 3:2, 4:3 e 1:1, e lacunas em ressonâncias como 2:1, 3:1, 5:2 e 7:3, conhecidos como Kirkwood Gaps (Moons, 1996; Nesvorný and Morbideilli, 1998; Tsiganis et al., 2002; Todorović, 2017). Essas ressonâncias podem produzir um comportamento caótico que aumenta a excentricidade orbital e/ou inclinação dos asteróides, causando desvios significativos de suas órbitas iniciais e potenciais encontros com a órbita de Marte (Wisdom, 1982).

Trabalhos anteriores mostram que os NEOs são objetos ejetados do cinturão principal através de processos dinâmicos complexos envolvendo movimento médio e ressonâncias seculares. O caos devido à sobreposição de MMRs afeta os corpos nas proximidades, levando-os a uma evolução dinâmica errática e caótica que transporta esses objetos à região dos NEOs (Wisdom, 1982; Dermott and Murray, 1983; Morbideilli, 1999; Morbideilli and Nesvorný, 1999; Milani et al., 2014; Dermott et al., 2021). Ressonâncias seculares, incluindo ν_5 , ν_6 e ν_{16} , também regem a evolução a longo prazo de pequenos corpos no cinturão de asteróides (Morbideilli and Moons, 1993; Froeschlé et al., 1997; Michel and Froeschlé, 1997; Ji et al., 2006). Além disso, a ressonância de Kozai-Lidov é um fator importante na evolução de asteróides na região próxima da Terra (de la Fuente Marcos and De la Fuente Marcos, 2016; Kozai, 1962).

Ademais, o efeito Yarkovsky é um fenômeno que desempenha um papel crucial

³ Legenda Figura 2: Distribuição de (a, i) no gráfico superior e (a, e) no gráfico inferior para $\sim 1.3 \times 10^6$ asteróides no cinturão principal com dados orbitais do Minor Planet Center (IAU-MPC, 2023). As regiões mais brilhantes representam uma maior densidade de objetos.

na evolução de objetos com diâmetros pequenos. É uma força não gravitacional que surge devido à absorção assimétrica e reemissão da radiação solar por um asteroide. Este processo leva a uma mudança ligeira, mas consistente, na órbita do asteroide ao longo do tempo (Rubincam, 1982). A magnitude do efeito Yarkovsky depende principalmente das propriedades físicas do objeto, como diâmetro, período de rotação, albedo e radiação solar na superfície do objeto, entre outros parâmetros de superfície (Farinella and Vokrouhlický, 1999; Bottke et al., 2000). Por exemplo, para um objeto de 1 km no cinturão principal, o arrasto devido ao efeito Yarkovsky é estimado em 10^{-4} au/Myrs (Bottke Jr et al., 2002; Delbo' et al., 2007), o que o torna o efeito mais importante e que mais afeta as órbitas de pequenos objetos do cinturão principal.

Devido ao arrasto lento mas constante no semi-eixo maior, o efeito Yarkovsky pode levar objetos de órbitas estáveis no cinturão principal para regiões de ressonância caótica chamadas rotas de fuga, que podem transportá-los para órbitas próximas da Terra (Bottke et al., 2002; Bottke Jr et al., 2006; Morbidelli and Vokrouhlický, 2003). No entanto, uma vez que os objetos grandes (diâmetro > 1 km) cruzam o pericentro de 1.3 ua e se tornam um NEO, o efeito Yarkovsky torna-se insignificante em comparação com as perturbações gravitacionais dos planetas terrestres, que são 5 ordens de magnitude maiores que o arrasto do Yarkovsky devido aos efeitos térmicos (Granvik et al., 2018).

Ainda, os objetos sob a perturbação do efeito Yarkovsky não têm a localização de suas rotas de fuga significativamente alterada, apenas as escalas de tempo em que a fuga ocorre (Granvik et al., 2017). Além disso, objetos que escaparam do cinturão principal não apresentam diferenças significativas na distribuição orbital quando estão sob influência do efeito Yarkovsky (Granvik et al., 2018). Portanto, embora o efeito Yarkovsky seja uma das perturbações mais importantes na dinâmica dos asteroides, ele pode ser negligenciado em alguns estudos sem grandes perdas nos resultados estatísticos.

O tempo de vida dinâmico estimado da população NEO é de 10 milhões de anos (Gladman et al., 2000), o que apoia a suposição de que esta população está em um estado estacionário e é constantemente reabastecida por objetos de regiões externas (Bottke Jr et al., 2002; Granvik et al., 2016, 2018). A distribuição da inclinação orbital da população NEO mostra que há uma taxa muito maior de objetos de alta inclinação na região dos planetas terrestres do que no cinturão principal, como mostrado na Figura 3⁴. No entanto, apenas uma fração dos NEOs de alta inclinação vieram de asteroides de alta inclinação no cinturão principal (Zain et al., 2020). Na verdade, estima-se que apenas cerca de 2% da população NEO no estado estacionário evolua para objetos retrógrados (Greenstreet et al., 2012a; Granvik et al., 2018). Além disso, existem vários trabalhos que mostram que, depois de chegarem do cinturão principal, os NEOs ainda podem se deslocar para diferentes partes do Sistema Solar e ter diferentes conjuntos de destinos (Gladman et al., 2000; Granvik et al., 2018; Siregar, 2010).

No entanto, várias questões interessantes permanecem sem resposta, levando a uma

⁴ Legenda Figura 3: Distribuição de (a,i) no gráfico superior e (a,e) no gráfico inferior para os asteroides do cinturão principal e população de NEOs com dados orbitais do Minor Planet Center (IAU-MPC, 2023). As regiões mais brilhantes representam uma maior densidade de objetos. Os pontos verde-púrpura representam os NEOs e os pontos preto-amarelos representam os asteroides do cinturão principal.

reavaliação do problema da grande evolução dinâmica conhecida do NEO. Como evoluem os grandes NEOs quando entram na região dos planetas terrestres? Seguirão caminhos preferenciais e como é que esta evolução afecta as suas vidas e destinos finais? Quais são os processos que levam ao aumento da inclinação que observamos na grande população conhecida de NEO? Qual o papel da inclinação no tempo de vida dos objetos na região NEO? Abordar estas questões é crucial para compreender a estabilidade e dinâmica a longo prazo da população de NEOs grandes conhecida.

Outro aspecto intrigante dos corpos pequenos do Sistema Solar é a presença de asteróides binários, sistemas nos quais dois corpos orbitam o seu centro de massa comum. A primeira descoberta de um satélite de asteróide foi feita pela espaçonave Galileo da NASA. Imagens do asteróide (253) Ida, tiradas durante um fly-by em agosto de 1993, mostraram uma pequena lua orbitando o asteróide que foi então chamado de Dactyl ([Chapman et al., 1995](#)). Desde então, sabe-se que quase 500 corpos menores têm pelo menos um satélite companheiro⁵.

Asteróides binários oferecem oportunidades únicas para explorar processos fundamentais, como formação de corpos planetários, dinâmica de colisão e interações gravitacionais ([Durda et al., 2004](#); [Pravec and Harris, 2007](#); [Scheeres, 2007](#); [Pravec et al., 2010](#)).

A Figura 4 ⁶ mostra a distribuição do diâmetro versus período de rotação do primário para as diferentes técnicas de detecção. Os retângulos representam os grupos binários de asteróides ([Pravec and Harris, 2007](#); [Pravec et al., 2010](#)). O Grupo A é composto por asteróides primários pequenos e de rotação rápida. O Grupo B contém sistemas com primários pequenos, mas binários com tamanhos semelhantes ($D_2/D_1 \sim 1$) que giram mais lentamente à medida que o diâmetro primário aumenta. O Grupo L é para objetos grandes e de rotação rápida.

No entanto, devido a limitações nas observações, alguns tipos de asteróides binários são detectados preferencialmente. Os objetos com grandes separações ou mais brilhantes são favorecidos no caso de imageamento direto, enquanto sistemas compactos são mais facilmente detectados usando a técnica fotométrica de curva de luz ([Merline et al., 2002](#); [Richardson and Walsh, 2006](#)) e as observações de radar são fortemente limitadas e só podem detectar com mais confiança asteróides binários próximos à Terra ([Ostro et al., 2002](#)). Além disso, ocultações estelares e sondas espaciais já foram utilizadas para detectar tais objetos ([Belton and Carlson, 1994](#); [Gault et al., 2022](#)), mas representam uma pequena contribuição para as estatísticas da população.

Em geral, os pequenos asteróides binários (diâmetro $\lesssim 20$ km) são provavelmente formados por algum processo de desprendimento de massa e reacumulação de material em órbita ([Pravec and Harris, 2007](#); [Walsh et al., 2008](#)).

⁵ <https://www.johnstonsarchive.net/astro/asteroidmoons.html> e referências contidas no site

⁶ Legenda Figura 4: Distribuição do diâmetro do primário versus período de rotação do primário para a população de asteróides binários conhecida. As cores representam as diferentes técnicas de detecção: Radar, Curva de Luz (LC), imageamento direto com óptica adaptativa (AOT), imageamento direto com o telescópio espacial Hubble (HST) e outras técnicas menos comuns, como ocultações estelares ou imagens com sondas espaciais. Os três grupos diferentes são indicados (A, B e L) dependendo do tamanho relativo e período de rotação dos objetos (ver texto).

A faixa de tamanho intermediário (20-100 km) está sub-representada, com apenas $\sim 5\%$ da população total conhecida. Vários modelos e observações sustentam que alguns desses objetos foram formados a partir da ruptura de um corpo parental (Descamps et al., 2009; Marchis et al., 2011). Acredita-se que um mecanismo semelhante forme Escaping Ejecta Binaries (EEBs) (Doressoundiram et al., 1997; Durda et al., 2004) que deveriam ser os fragmentos resultantes de uma colisão em baixa velocidade relativa.

No entanto, ainda existem algumas lacunas de conhecimento sobre a origem e formação de sistemas binários de asteróides e a sua evolução dinâmica. Para compreender melhor esses objetos, precisamos de uma amostra estatisticamente significativa e diversificada de sistemas binários, que atualmente é limitada. Embora a detecção de asteróides binários usando dados astrométricos não possa resolver todos os problemas, lidar com o viés observacional e preencher todas as lacunas, ela pode auxiliar na detecção de objetos em espaços inacessíveis para outras técnicas de observação (Pravec and Scheirich, 2012).

A astrometria desempenha um papel crucial na compreensão da estrutura e dinâmica dos corpos do Sistema Solar, e do universo como um todo. Ele se concentra na medição precisa das posições e movimentos de objetos celestes no céu com o objetivo de determinar suas distâncias, movimentos próprios e paralaxes. Os dados astrométricos dos asteróides são essenciais para prever as suas posições futuras e avaliar potenciais riscos de colisão com a Terra, por exemplo.

A missão Gaia é um projeto da Agência Espacial Europeia (ESA) lançado em 2013 com o objetivo principal de realizar medições astrométricas precisas para todas as fontes de luz no espaço com magnitude $G \gtrsim 20$. O Gaia DR3 forneceu dados astrométricos de alta precisão para mais de 150.000 asteróides, o que permite procurar satélites de asteróides, conforme previsto durante o desenvolvimento da missão (Mignard et al., 2007; Pravec and Scheirich, 2012).

A detecção de uma assinatura astrométrica devido a um companheiro de asteróide já foi encontrada em alguns casos (Tanga et al., 2022; Ortiz et al., 2011). Porém, nesses estudos, a presença de um satélite já havia sido previamente confirmada por outras técnicas de detecção. Felizmente, em Tanga et al. (2022) mostramos evidências de que a altíssima precisão astrométrica fornecida em Gaia DR3 é alta o suficiente para permitir a detecção do sinal astrométrico gerado por um asteróide companheiro, usando o asteróide (4337) Arecibo como exemplo. Portanto, no trabalho apresentado nesta tese, realizamos uma busca cega por binários astrométricos nos dados astrométricos dos asteróides no Gaia Data Release 3 (DR3).

Este esforço de investigação multifacetado visa aumentar a nossa compreensão dos corpos menores do Sistema Solar, das suas propriedades físicas e evolução dinâmica. Os conhecimentos obtidos com esta investigação têm amplas implicações, não apenas para estratégias de proteção planetária, mas também para melhorar a nossa compreensão da mecânica celeste, da formação planetária, da exploração espacial e da história do Sistema Solar.

A minha tese explora a evolução orbital e a detecção de diferentes classes de corpos menores no Sistema Solar. Do estudo da evolução dinâmica orbital dos NEOs ao desenvolvimento de um método para detecção astrométrica de asteróides binários, reúno

um conjunto de estudos que encerram um conjunto emocionante de resultados. Apresento trabalhos de pesquisa, em diferentes estágios de andamento, nos quais os projetos foram desenvolvidos durante meu doutorado. Os capítulos abordam temas independentes entre si.

Este trabalho está estruturado da seguinte forma:

- No Capítulo 3 eu apresento um estudo da evolução dinâmica dos grandes NEOs conhecidos e o artigo onde estudamos a evolução da inclinação orbital da mesma população de grandes NEOs conhecidos. Além disso, faço algumas discussões gerais sobre os trabalhos apresentados e resultados complementares não incluídos em nenhum dos trabalhos enviados para publicação. Em seguida, tiro as conclusões deste estudo e comento os passos futuros em que pretendemos trabalhar.
- No Capítulo 4 contextualizo brevemente o trabalho de detecção astrométrica de asteróides binários usando dados do Gaia DR3. Em seguida eu apresento o artigo em submissão sobre o tema, faço alguns comentários finais sobre trabalho e sobre os próximos passos.
- Finalmente, no Capítulo 5, eu apresento as conclusões principais dos trabalhos discutidos e os pontos chave da tese.

3 Near-Earth Objects' dynamical evolution

3.1 Contextualization

To answer a few of the open questions about NEOs and provide a comprehensive understanding of their dynamical evolution, this research takes a detailed approach to this topic. A carefully curated debiased population of 985 large known NEOs, with diameters greater than 1 km, is studied. The trajectories and fates of these NEOs are meticulously tracked through numerical integration techniques, simulating their motion over up to 100 million years. This extensive exploration allows for a thorough investigation of the dominant evolutionary pathways, estimation of half-life times for NEOs in various scenarios, statistical analysis of their ultimate fates, and determination of the role that the orbital inclination plays on the evolution of the large known NEO population. Additionally, in a complementary analysis, we explore the group of objects that collided with the planets in my simulations, their impact rates and orbital characteristics. Finally, preliminary results and analysis on the transport of large NEOs to the inner Venus and inner Mercury zones are presented and discussed.

The papers presented in this chapter are complementary to each other.

In the paper entitled "The Known Large Near-Earth Objects' Highways: dynamical evolution, fates and lifetimes", in Section 3.2, we present a review of the dynamical evolution of the known population of NEOs with diameters larger than 1 km where we determine the most common routes that these objects take while moving through the Solar System and their respective fates. This work was recommended for publication at EPJS by the guest editor and is currently awaiting the editorial board's final decision.

In Section 3.3 I present the paper entitled "On the Orbital Inclination Evolution of the Current Large NEOs", which analysed the role of the orbital inclination of the known large NEO population in the orbital evolution of the objects. Results show that it is not only related to their lifetime but also that there is a preferential range of inclinations to favour the survival of NEOs. This work was also recommended for publication at EPJS by the guest editor and is currently awaiting the editorial board's final decision.

Section 3.4 presents discussions about some topics in the works presented in the previous sections and introduces complementary results and analysis not included in any publications at the moment.

Finally, Section 3.5 presents the conclusions of this research and the works I aim to develop in the future on the studied subject.

3.2 The Known Large Near-Earth Objects' Highways: dynamical evolution, fates and lifetimes

The 'Known Large Near-Earth Objects' Highways: dynamical evolution, fates and lifetimes

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Submitted on 26 April 2023, Revised on 2 August 2023

Abstract

It is well known that the Near-Earth Objects population is sustained by bodies that migrate inwards from the main asteroid belt and outer regions of the Solar System. In this work, we aim to revisit the dynamic evolution of the NEO population inside the Solar System using a known debiased population of large objects. Therefore, we separate the phase space into five different regions: Near-Earth Objects (NEO), Main Asteroid Belt (MAB), Jupiter Family Comets (JFC), Centaurs (CEN) and Trans-Neptunian Objects (TNO). We performed numerical simulations for 985 NEOs for 100 Myrs and tracked their transferences between regions to determine the most common routes and fates for this population. The results show that solar thermal disruption is the most efficient mechanism to remove NEOs because 70% of the studied objects are led to this fate. Also, 13% of the objects are ejected from the Solar System, representing a significant contribution of interstellar minor bodies from the NEO population. We find that, during their dynamical evolution, more than half of the objects are first transferred to the JFC region and an even larger percentage of them make their way out from the Solar System through it. There is also a significant frequent exchange of bodies between NEO and MAB regions. Almost 30% of the bodies move to the MAB region, but less than 1% of them end their lives inside it, so it seems that for this sample of objects, MAB is a transitional region where escaped NEOs briefly pass through. We also found that only about 14% of the bodies never leave the NEO region. From those, about half of them collide with the terrestrial planets, while the remaining either survive for the whole integration of 100 Myrs or move to a low pericenter orbit. Additionally, we show that almost 10% of the studied sample can reach the CEN region and remain there for a substantial amount of time, telling a different side of the story for the NEO population.

1 Introduction

From meter-sized asteroids inside Venus' orbit to dwarf planets beyond Neptune, the Solar System presents us with a zoo of possibilities for different minor bodies and they are usually classified by their orbital characteristics. For instance, the Trans-Neptunian Objects (TNO) with semi-major axes larger than 30.1 au, the Centaurs between the orbits of Jupiter and Neptune, the Main Asteroid Belt between the orbits of Mars and Jupiter, and the Near-Earth Objects inside the terrestrial planet's region.

In the past decades, it has been shown that the transport of asteroids from some outer regions to terrestrial planets' neighbourhoods is not only possible, but it is also common [17; 3; 32; 2; 40; 42]. Essentially, the asteroids that reach the region of the terrestrial planets compose the population of Near-Earth Objects (NEO).

Many previous works show that most of these

objects in the NEO population came from the main asteroid belt (MAB) [34; 37; 40]. The most significant part from the inner MAB, but also the outer MAB and JFC are the source for the population [20; 4; 21; 13; 25].

Furthermore, even Centaurs [23; 50] and Trans-Neptunian objects (TNO) [30; 46; 37; 1] play a role in sustaining the NEOs. Considering a population of 117 objects, Gladman et al. (2000)[16] estimated the well-accepted half-life (or median life) for these bodies to be about 10 Myrs, meaning that half of the studied objects are gone after this period.

We know that the objects in the inner Solar System can move among the regions and classes, but what is the actual evolution of these bodies after becoming NEO? Are there any preferential routes for their evolutions? How does it affect their half-life time and final fates? In the present work, we readdress this problem by studying the dynamical evolution of a debiased population

with almost 1000 current known large ($> 1\text{Km}$) Near-Earth Objects. We follow their paths and fates through numerical integration for up to 100 million years. An analysis of these simulations indicates the main routes of evolution, the half-life time in each case, and the statistics of their final fates.

The following section presents how we delimited the regions of the space in terms of semi-major axis versus eccentricity. Section 3 describes how were performed the numerical simulations. The results and analysis are shown in sections 4 and 5. Section 6 discusses the results in a steady-state situation. Our final comments are presented in the last section.

2 Regions of the Space

A NEO is an object that has its orbit strongly affected by the terrestrial planets' gravitational effect, i.e. has a pericentre $q < 1.3\text{ au}$, and there is no formal agreement on the upper limit for the apocentre. The frequent close encounters suffered by the NEOs with the terrestrial planets, among other secondary effects, result in a chaotic orbital evolution of these celestial bodies [22; 31; 44].

The NEO region is embedded in countless mean motion resonances [15]. The author shows that these resonances contribute to removing bodies from that region, but some objects could survive if they are lucky enough to dodge close encounters with Mars between 1.5 and 2 au.

Through a few different resonant mechanisms [35; 36], bodies in the main belt usually dynamically evolve into chaos and have a few different fates. A few works study the primary sources of the debiased NEO population and find that the inner main belt is the primary origin for these objects [20; 21; 4].

Asteroids in the main belt can be transferred to an Earth-crossing orbit or eliminated by going to a Jupiter-crossing orbit or impacting the Sun [17]. Bodies in the terrestrial planets' region can be affected by secular resonances within 2 au [31] and develop high inclinations, or they can return to the main belt through gravitational perturbation from the terrestrial planets and then hit the Sun or be ejected from the Solar System [11].

In Gladman et al. (2000) [16], the authors selected 117 objects with high-quality orbits at that time, with pericentre $q < 1.3\text{ au}$. They numerically integrated the orbits of these particles under the gravitational effect of the planets for 60 Myrs. They found that the median life for the studied sample was 10 Myrs, where more than half of the sample was eliminated by the Sun-grazing process.

As mentioned previously, beyond the NEOs there are also the asteroids in the main belt between Mars and Jupiter; the bodies with short-period cometary orbits that are majorly affected by Jupiter are classified as JFC¹; Centaurs, which are the minor bodies between Jupiter and Neptune; and those beyond Neptune's orbit, called TNOs. As the exact limits of these regions have some disagreements from one reference to another, and our goal is not to classify the objects but only follow their "big picture" evolution through the Solar System, we use a rough approximation.

Therefore, in our work we consider that these regions are bounded as shown in Figure 1. They are delimited by semi-major axis and eccentricity, independently of the orbital inclination. To obtain JFC region limits, we looked for $a \times e$ values using a Tisserand parameter² between 2-3, and assuming inclination $i = 0^\circ$, regardless object's current inclination. In our analysis, the NEO region is bounded by $T > 3$ and $q < 1.66\text{ au}$. Pericentre $q > 1.66\text{ au}$ and apocentre $Q < 4.45\text{ au}$ defines the main asteroid belt (MAB) region.

JFC is limited by $3 \leq T \leq 2$, and a body with $q > 6.0\text{ au}$ and $q < 33.42\text{ au}$ is inside the centaur region. Bodies with $q > 33.42\text{ au}$ are inside the TNO region. Our goal is to analyse dynamically the evolution of bodies among regions, despite their physical classification between asteroids and comets. So, for instance, if a body is inside the JFC region it does not necessarily mean that it will be considered a comet in our work, only that it spends some time mainly under the gravitational influence of Jupiter regardless of its dynamical classification.

Note that the region between $1.3 < q < 1.66\text{ au}$, which corresponds to the region of the population of Mars crossers, is not considered as one particular region in our analysis, since it is a transitional region for objects transitioning between MAB and NEO regions.

3 Numerical Simulations

Our simulations aim to analyze the dynamical evolution of an unbiased population of known

¹JFC definition varies based on the orbital period, on the aphelion, perihelion, and/or on the Tisserand parameter throughout the works [10; 43; 26]. There is no formal agreement in the community about which are the exact boundaries of the JFC zone.

²Tisserand parameter is defined as:

$$T = \frac{a_{\text{Jup}}}{a} + 2\sqrt{\frac{a}{a_{\text{Jup}}}(1 - e^2)} \cos i$$

where a, e and i are the semi-major axis, eccentricity and inclination of the small particle affected by Jupiter's perturbation, and a_{Jup} is Jupiter's semi-major axis.

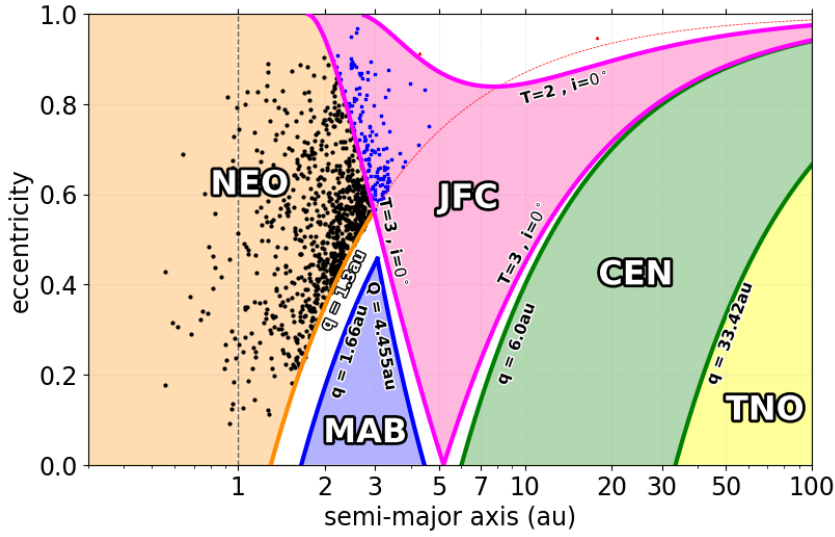


Figure 1: Plot of a versus e of the initial conditions of the NEOs with an estimated diameter of at least 1 Km and the assumed bounds of regions studied in this work. Each dot represents one initial condition for one NEO. The black dots are the bodies with initial $a \times e$ lying inside the NEO region only. The blue dots represent the bodies on the overlap between JFC and NEO, and the red dots are bodies with initial conditions lying outside the defined regions.

NEOs, their paths, fates and lifetimes over a large time span.

On June 29th, 2020, we accessed ESA NEO³ database [41] and obtained initial conditions for our simulations. There were almost 30,000 NEOS confirmed at the date, but they are mostly small bodies. Therefore, to have an unbiased population of NEOs, we chose to use the estimated body's diameter as a parameter to select the bodies. We chose those with an estimated diameter of at least 1 km resulting in a population of 985 bodies. As almost all the bodies larger than 1km are already known, that is an important factor to ensure that the studied population is unbiased.

The Yarkovsky effect is the most dominant non-gravitational force that affects the orbits of NEOs [39]. However, close encounters between the NEOs and the planets happen frequently, so the changes in the objects' orbits due to the gravitational perturbation arise much faster than the Yarkovsky timescale. It is important to note that we are not focused on the dynamic evolution of one specific object. We are interested in the statistical evolution of a population. The Yarkovsky effect has a significant influence on the flux and timescale of objects escaping the main belt, but they do not affect the location of the escape routes [19]. Granvik et al. (2018) [20] found that the orbit distribution of the steady-state NEO population does not present a significant change when escaping objects from the main belt are under the Yarkovsky effect influence. Furthermore, the authors estimate that the gravitational

perturbation from the planets in km-size NEOs is about 5 orders of magnitude more significant than the thermal forces [20]. Therefore, since the Yarkovsky effect would maybe have a more detectable influence only on the timescales, we did not take it into account.

$q <$	Initially inside NEO		All bodies	
	$R_{\odot}$	0.058 au	$R_{\odot}$	0.058 au
Survive	8.6%	8.0%	7.5%	6.9%
Collision with Planets	9.4%	8.5%	8.3%	7.5%
Ejection	46.8%	13.1%	49.4%	16.9%
Sun-grazing	35.2%	70.4%	34.8%	68.7%
Median life ($\times 10^6$ years)	9.0	7.6	6.5	5.3

Table 1: Percentage of fates and lifetimes for different constraints. The first two columns show the results obtained from the group of objects that were initially inside the NEO region only, the two following columns show the results for all the 985 objects in the sample. The percentages are given concerning the number of objects in the sample in each case, so for “initially inside NEO” there are 839 objects and for “All sample” there are 985. Columns “ $q < R_{\odot}$ ” represent the data from the analysis considering that the limit assumed for a Sun-grazing object is the physical radius of the Sun, and the columns “ $q < 0.058au$ ” represent the results when the limit is the minimum distance for thermal destruction for km-size objects, so these objects would be disrupted before hitting the Sun.

The initial conditions are shown in Figure 1 as the black dots. Coloured areas represent the different minor body regions considered in our

³<http://neo.ssa.esa.int>

study, as discussed previously. The bodies in our sample studied have different initial orbital inclination values, but it does not affect their classification, which depends only on semi-major axis and eccentricity values. Therefore, although we use the bodies' inclinations in the initial conditions, we decided to consider only the bodies' semi-major axis and eccentricity to analyze the results on the transferences and paths.

For this work, we used the Mercury package [5] with a Hybrid integrator that uses a second-order mixed variable symplectic map when a body is far from the others and a Bulirsch-Stoer integrator when two bodies get closer than 3 Hill's radii. We used our sample of 985 bodies, plus the 8 Solar System planets and the Sun with positions for the same epoch. One might argue that other objects, such as dwarf planets, could contribute to the evolution of objects in the inner Solar System. It was proven, for instance, that Ceres can transport objects in the main belt to the NEO region [27]. However, it was also shown that they have a minor effect on objects outside the main belt [49] and its significance is mostly seen on asteroid families that are affected by secular resonances [38]. Therefore, we chose not to include them in the simulations.

We considered the minor bodies to be test particles, so they were affected by the massive bodies but did not affect each other. We run each simulation for up to 100 million years and the base simulation time step is 2 days. The NEOs were only eliminated from the simulation once they collided with a massive body or their orbits became hyperbolic (ejected from the Solar System).

4 Fates and Lifetimes

First, we want to study the lifetime and fates of the sample. To analyze NEOs' dynamical evolution we used the initial sample mentioned in section 3. But from the 985 bodies, almost 10% have the semi-major axis and eccentricity initially inside the JFC region. Although these bodies' classification is NEO, they are strongly affected by Jupiter and using them in the analysis can generate misconceptions about orbit evolution.

Therefore, we decided to separate the objects whose orbits are initially majorly affected by terrestrial planets (hereafter "initially NEO") from those initially majorly affected by Jupiter, which are the blue dots in Figure 1 (hereafter "initially JFC"). Hence, for most of the analysis, we did not take the initially JFC bodies into account and we discuss this group of objects separately in Sec. 5.4. There are also two bodies with initial conditions that locate them outside the boundaries of the regions we defined (red dots in Figure

1). So, since we also neglected them in the initially NEO sample, we end with 839 NEOs left.

It is common for works that study NEOs evolution to eliminate objects by physical collisions or Sun-grazing orbits, by the assumption that they will hit the Sun in a short time after their pericenters become smaller than the Sun's radius [16; 11; 21; 20]. However, it is known that thermal effects can destroy objects before the collision with the Sun once they reach a critical separation and for Km-size objects this distance was estimated at approximately 0.058 au [18; 20]. Therefore, we decided to compare the statistics of fates and lifetimes using both assumptions, the usual Sun-grazing approach and the thermal disruption by assuming that the asteroids will soon be destroyed if their pericenters are smaller than the km-size disruption limit.

Table 1 shows the results for the percentage of fates for the different scenarios studied and the respective half-life of the samples. We find that some bodies that survived and collided with planets in the Sun-grazing scenario would have suffered disruption and been eliminated before having this fate, but they represent less than 1% for each case. As will be discussed in more depth further in this work, this population of survivors and impactors tend to have less chaotic orbits, so their results are expected not to change significantly. However, for the other cases, we notice that when we take into account the loss of objects due to thermal effects we find that 2/3 of the bodies that are supposedly ejected from the Solar System would be first destroyed when crossing 0.058 au. It means that thermal disruption is the most efficient mechanism to remove NEOs.

Since the disruption limit is not strictly the value used here, the rates can present small variations because it depends mainly on the body's size, but also the albedo. Also, if we take into account not only the objects initially inside the NEO region but all the sample, the number of ejections increases while the other rates decrease due to the presence of the objects initially inside the JFC region that are more likely to be ejected and leave the region faster than the rest of the sample (as will be shown in Section 5.4).

Therefore, we can conclude that the percentage of the large NEO population that collide with the Sun is roughly around $52\% \pm 18\%$ and that the rate of ejection is close to $32\% \pm 18\%$, depending on the parameters chosen for the analysis. For the other fates that are not significantly changed, we notice that the rate of collision with planets is always larger than the rate of survivors.

The results presented in " $q < R_\odot$ " columns in Table 1 use a similar approach as in [16], and the comparison shows that we find a much higher

rate of ejections than Sun-grazing objects in that case. However, the results the authors obtained are within the values we find in our results from the two scenarios explored.

We believe that there are a few possibilities to explain the difference in the results, which are: 1- they used a considerably smaller sample of objects; 2- due to observational limitations at the time, their sample could be strongly biased, unlike the $> 1\text{Km}$ population we study; 3- they integrated for 60 million years while we did for 100 million years, so it could change the results, for instance, a large number of survivors could have different fates; and most importantly, 4- we believe that the authors used the radius of the Sun a few times larger than the real value since their rates of ejection and Sun-grazing lie in the middle of the interval we find for these fates considering both extremes, the radius of the Sun and the km-size disruption limit.

To obtain the population median life, [16] count the total lifetime of an object no matter where it is in the Solar System, using the Sun-grazing scenario, and find that the NEO population median life is 10 million years. Using the same approach, we obtain a half-life time of the population of 6.5 Myrs, about half of the value found by Gladman et al. but still close enough to agree. Compared with the values we obtained for the initially NEO sample the values are even closer.

Using a different procedure, we took a more generous limit of pericenter for a body to be classified as a NEO and considered $q = 1.6\text{ au}$ (Mars' apocentre) as the edge. We count only the lifetime of these bodies while their pericenters are still within that limit, i.e., if the object spends more than 5000 years outside the NEO region it will not be considered a NEO anymore and is eliminated.

In this approach, we found a half-life time of 2.7 million years, which is much smaller than the expected lifetime we usually assume. That small lifetime is because the largest part of the objects leaves the NEO region in a short time, so the half-life of the population decreases considerably. So if the assumption is that objects can only be classified as NEOs while they are within $q < 1.6\text{ au}$, the population's lifetime is much smaller than the well-accepted half-life time of 10 million years.

The half-life times change with the different constraints and populations considered, as shown in Table 1. The lifetime for the entire sample when accounting for the thermal disruption is about 5.3 million years. In comparison, the "initially inside NEO" objects, without accounting for the thermal effects, have a median life of

9 million years, which is almost two times larger than the value for the "All sample" case and is close to the well-accepted 10 Million years [16].

As mentioned previously, the objects initially inside JFC tend to be ejected on a larger scale than the rest of the sample, therefore their lifetimes are much shorter, and that is one of the reasons why the median lifetime is smaller for the "All sample" cases, and even shorter when taking the thermal disruption into account. But, in general, the lifetimes for all cases are still in the same order of magnitude and are not massively different. It means that the thermal disruption does not affect the trajectories of the NEOs in the Solar System, nor significantly change the time in which the objects will be lost, just their fates.

5 Initially NEO Dynamical Evolution

To obtain the results with less bias possible, we choose to work only with the initially NEO sample and take into account the thermal disruption, as presented in the previous section. We now aim to study the evolution of the objects in the Solar System and obtain their common routes. We use an output step from the simulations of 2.5 years and assume that a body moved to another region, as described in Figure 1, after 2,000 steps inside another region. It means the object has a residence time of at least 5,000 years inside the new region. It is enough time for objects to have, at least, a few hundred orbital periods inside the region, which means that they were permanently transferred during this time. However, it does not necessarily mean that this body also changed its minor body classification. We are interested only in the dynamical evolution and transfers among the regions, not in reclassifying these objects. As we are not looking for fleeting changes, this assumption deals with the bodies under resonant effects that repeatedly cross the regions' boundaries and those that need to cross other regions before being ejected or hitting the Sun.

The results presented in Table 2 show the fates and percentage of transferences for the filtered sample of NEOs. About 14% of the bodies never leave the NEO region, which means that approximately 85% of the large NEO population studied migrate outwards and spend a considerable amount of time in different regions.

More than half of the objects are first transferred to the JFC region, and 9% to the CEN afterwards. 28% of the bodies go to the MAB region, and all of them go back to NEO before a

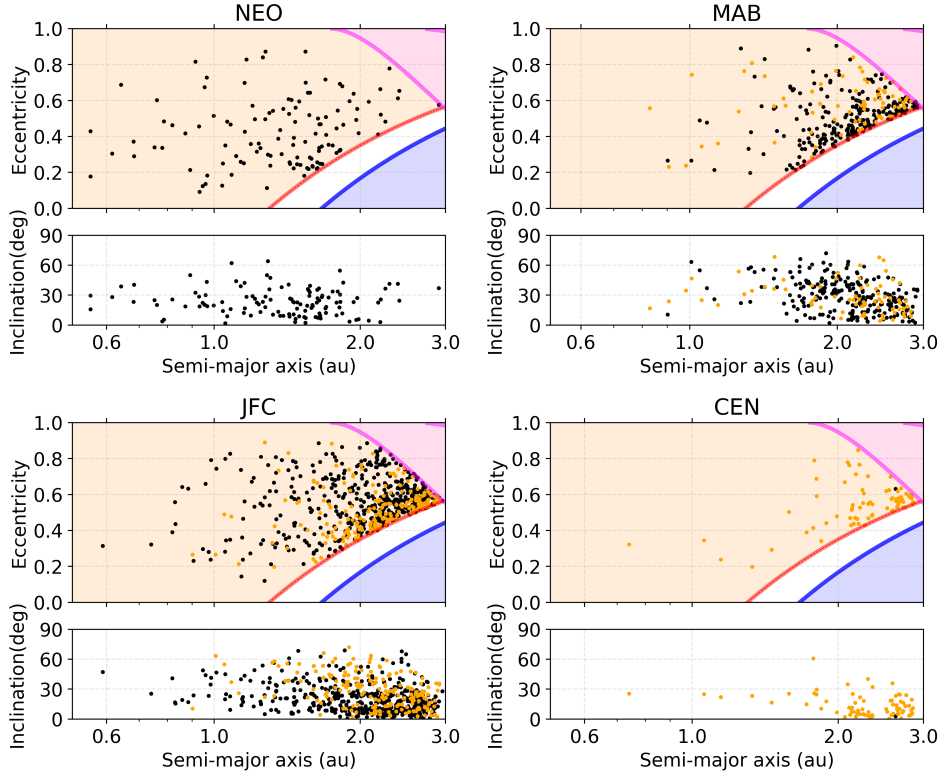


Figure 2: Plots of a versus e (top) and a versus i (bottom) of the initial conditions of the simulated bodies transferred to a different region. Each dot represents one initial condition for one body. The plot for NEO represents the bodies that stayed in the region during their entire life. For the other plots, the black dots represent the bodies transferred from NEO in the 1st transference, while the orange dots represent the bodies transferred to the current region through the second transference.

large part moves to JFC. We notice that the NEO and MAB regions have a heavy exchange of objects.

Also, counting all the registered transferences we find that more than 80% of the objects resided at some stage within the JFC region, and most of them ended up being destroyed by the thermal disruption from the Sun. So, JFC seems to be the region that leads the objects to their most common fate. Additionally, there is one object that is found to reach the CEN region directly out from NEO. That case may be simply the consequence of specific initial conditions, but a complementary study is needed to determine the statistical relevance of this result.

Figure 2 shows the initial conditions in the semi-major axis, eccentricity and inclination of the studied bodies as presented in Table 2. We can notice that for the objects that never leave the NEO region, the top left plot in Figure 2, there seems to be a lack of objects with pericenters close to 1.3 au (red line) and a larger number of objects interior to the Earth.

It explains why these objects tend to survive longer and can remain inside the NEO region for their entire lives. For the objects that are transferred, apparently, there is no clear pattern of initial conditions that indicate that a body will

be transferred to some specific region, especially for the inclinations. It shows that the initial inclinations do not seem to play a major role in the dynamic evolution of this population.

5.1 Resonances in NEO and MAB

It has been widely studied that resonances are the main mechanism causing the exchange of bodies between MAB and NEO [17; 35; 37]. Mean motion resonances (MMR) are all over the NEO region, but those with Venus and Earth tend to dominate up to 1.5 au [15]. The supplementary video ⁴ show the first 250×10^3 years of the evolution of the bodies that survived a 100 Myrs and never left the NEO region (Always NEO).

It shows that the object's orbital eccentricities vary widely while the semi-major axes are constrained, which is a characteristic of objects under MMR and/or secular perturbation effects from Jupiter such as the Kozai mechanism [6; 28]. We also notice that objects tend to concentrate more between 1.5-1.8 au and even though these bodies spread over 100 million years, the concentration of bodies in this area remains, as shown in Figure 3.

⁴Animation of Always NEO survivors' evolution: https://bit.ly/NEOs_evo1_250kyrs

	Total (%)	Survive (%)	Sun- grazing (%)	Ejected from SS (%)	Collided with a Planet (%)	Back to NEO anytime (%)
Never leave the NEO region						
Always NEO	14.30 (4.74)	4.05 (0.04)	2.74 (3.31)	0.00 (0.00)	7.51 (1.39)	—
Transference to second region						
NEO→MAB	28.01 (27.94)	3.58 (0.04)	20.26 (24.47)	3.22 (3.26)	0.95 (0.18)	28.01 (27.94)
NEO→JFC	57.57 (67.20)	0.36 (0.00)	47.44 (57.29)	9.77 (9.91)	0.00 (0.00)	46.84 (54.68)
NEO→CEN	0.12 (0.12)	0.00 (0.00)	0.00 (0.00)	0.12 (0.12)	0.00 (0.00)	0.00 (0.00)
Transference right back to NEO region						
NEO→MAB→NEO	27.18 (26.94)	3.58 (0.04)	19.43 (23.46)	3.22 (3.26)	0.95 (0.18)	—
NEO→JFC→NEO	33.13 (38.31)	0.36 (0.00)	26.22 (31.67)	6.56 (6.65)	0.00 (0.00)	—
Transference to a third region						
(NEO→MAB) — — →JFC	23.12 (27.03)	0.12 (0.00)	19.67 (23.75)	3.22 (3.26)	0.12 (0.02)	20.02 (23.41)
(NEO→JFC) — — →MAB	8.70 (9.80)	0.36 (0.00)	6.91 (8.35)	1.43 (1.45)	0.00 (0.00)	7.75 (8.73)
(NEO→JFC) — — →CEN	8.94 (9.82)	0.00 (0.00)	3.93 (4.75)	5.01 (5.08)	0.00 (0.00)	0.24 (0.26)
(NEO→CEN) — — →JFC	0.12 (0.12)	0.00 (0.00)	0.00 (0.00)	0.12 (0.12)	0.00 (0.00)	0.00 (0.00)

Table 2: Percentage of bodies' fates according to each transference between regions for the initially NEO sample. The first line shows the results for the objects that never left the NEO region for more than 5,000 years, and we refer to them as "Always NEO". The following block shows the transfereces from the NEO region straight to a second region, as indicated. The third block shows the objects that, after being transferred to a second region, return to NEO before going to some other region. The last block shows the results of the bodies that were transferred to a third region, as indicated, and may or may not have gone back to NEO before this transference. The transfereces " $NEO \rightarrow CEN \rightarrow NEO$ ", " $(NEO \rightarrow MAB) - - \rightarrow CEN$ " and " $(NEO \rightarrow CEN) - - \rightarrow MAB$ " are not included because they are null. The first column represents the total percentage of bodies that moved to the region indicated. The following 4 columns represent the rate of bodies in each fate. The last column shows the percentage of bodies that returned to the NEO region at any point in their lifetimes. The first 4 lines add to 100% of the studied NEOs. The remaining lines are subsets of data derived from them. For instance, the 27.18% of the sample in " $NEO \rightarrow MAB \rightarrow NEO$ " represents about 97% of the bodies in " $NEO \rightarrow MAB$ ", while the 23.12% of objects in " $(NEO \rightarrow MAB) - - \rightarrow JFC$ " represents roughly 82.5% of objects from " $NEO \rightarrow MAB$ ". The values out of parenthesis are the percentages obtained for the 839 objects in the sample, and the values in parenthesis are the weighted results assuming the population is in a steady state, as discussed in Section 6.

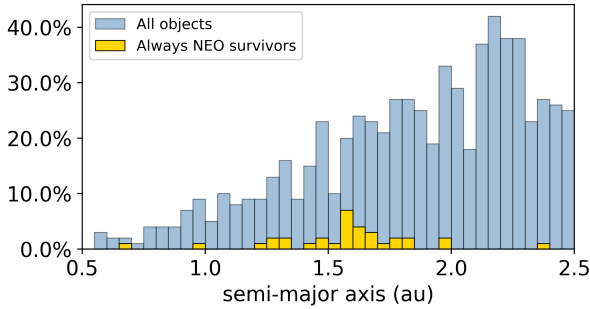


Figure 3: Histogram showing the semi-major axis distribution of the population initially NEO between 0.4 and 2.5 au (in blue) in comparison with the distribution of the surviving objects in "Always NEO" group at the end of the 100 Myrs simulation (in yellow).

About 1/3 of the "Always NEO" survivors remain within these limits until the end of the simulation, which is very different from the initial distribution of semi-major axes that have a larger concentration of objects between 2.1 and 2.4 au. Figure 4 shows the initial and the final distributions of inclination and semi-major axis of the "Always NEO". We notice that over time some of

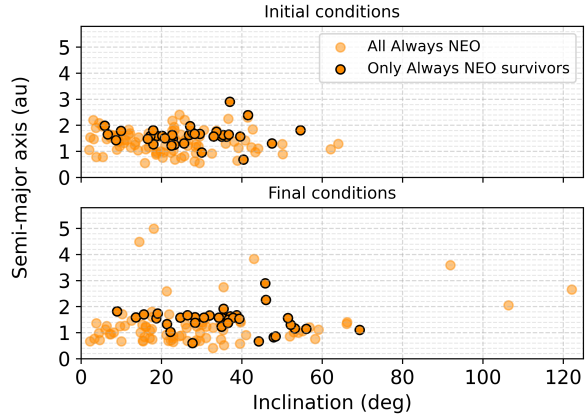


Figure 4: Plots showing the initial (top) and the final (bottom) distributions of inclination versus semi-major axis for the objects in the "Always NEO" group.

the objects tend to gain inclination and get further in the semi-major axis.

But most of them tend to stay close to the initial distribution, especially the survivors. Furthermore, the majority of the survivors have high inclinations (> 20 degrees) at the end, and al-

most half of them lie around 1.5 au. The high inclination is another factor that makes it more difficult to have close encounters with the planets and hence they are more likely to survive for longer periods.

Objects with semi-major axis smaller than 1.4 au are most likely to be eliminated from the region because of the strong resonances with Venus and Earth, forcing them to cross the planet's orbits and collide or have close encounters, hence having fewer chances of surviving. The objects beyond 1.8 au tend to be more affected by Jupiter's secular perturbation since they're closer to the planet.

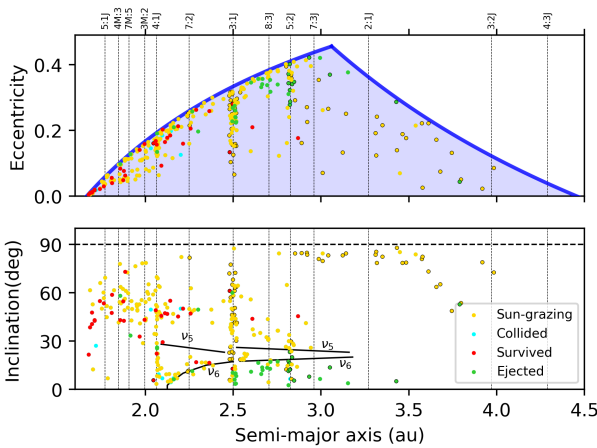


Figure 5: All bodies transferred to the MAB region as a first or second transference. The vertical black lines indicate the location of MMRs. On the bottom plot of the semi-major axis versus inclination, the black thicker lines show the approximate location of ν_5 and ν_6 secular resonances, as indicated on the plot. The coloured dots represent the position of each object after 5000 years inside the MAB region and the final fates are indicated by the different colours. The dots with no border represent the objects that came directly from the NEO region and those with black borders indicate the objects that came from different regions.

In such conditions they cross Jupiter's orbit more frequently or fall into some of the strong resonances with the planet, leading them to leave the NEO region. The bodies in the 1.4-1.8 au vicinity are also affected by resonances and secular perturbation from Jupiter. [15] shows that the NEO region has many MMRs, but since the stronger resonances such as 1:2 MMR with Earth and 5:1 MMR with Jupiter are well separated, this zone is not strongly affected by the chaos that comes from resonances overlapping.

Also, since there are no planets close it is less likely to have close encounters. Additionally, as mentioned previously, these objects tend to have larger inclinations. All these factors seem to explain why this part of the NEO region tends to accumulate the largest portion of surviving ob-

jects.

As we see in Figure 5, most of the bodies concentrate up to 3 au, and beyond they tend to spread more. It also shows several objects under the resonance sticking phenomena, where they seem to accumulate mostly around the resonances 4:1, 3:1 and 5:2 with Jupiter and around ν_6 , as shown in the inclination plot.

These bodies are more likely to be ejected from the Solar System or hit the Sun [11], probably due to the great increase in eccentricity forced by the resonances. It is also interesting to note the line of bodies with high inclinations close to 90 degrees that could become retrograde objects [21; 24], but that analysis is not in the scope of this work.

The MAB region is also embedded in MMRs. Beyond approximately 2.9 au, the objects are affected by the chaos caused by overlapping resonances with Jupiter, which may send them to Mars-crossing or near-Earth orbits [48; 7]. The innermost part of the MAB region is affected by Jovian resonances as well, but Mars also plays an important role in increasing the number of strong resonances overlap, responsible for the chaotic dynamical evolution and delivery of bodies into NEO region [36; 33; 8].

The objects closer to the inner border of the MAB region ($a < 3$ au), which would probably be classified as Mars-Crossers (MCs), are more likely to survive or hit planets due to the MMRs with Mars and secular resonances than the objects further in the region, as expected [49].

The objects in the main belt injected in resonances, especially the 3:1 and 5:2 MMR with Jupiter and ν_6 , usually have short dynamical lifetimes, not larger than a few million years. But the time to cross Mars' orbit is typically in the order of thousands of years [17; 32].

It explains why the transference between NEO and MAB regions happens frequently and why these objects rarely end their lives inside the MAB region.

5.2 Main Routes

The results show that, as expected, the NEOs have all sorts of evolutionary paths and fates in the Solar System, but some of them seem to be more frequent than others. Therefore, we can estimate the most likely pathways that the NEO population take, as summarised in Figure 6, are:

- **Route Always NEO** : Bodies that never leave the NEO region, i.e. never spend more than 5000 years inside other regions than NEO, represent about 14% of the studied sample. This route holds almost all collisions with planets and is the most likely fate for this group. The re-

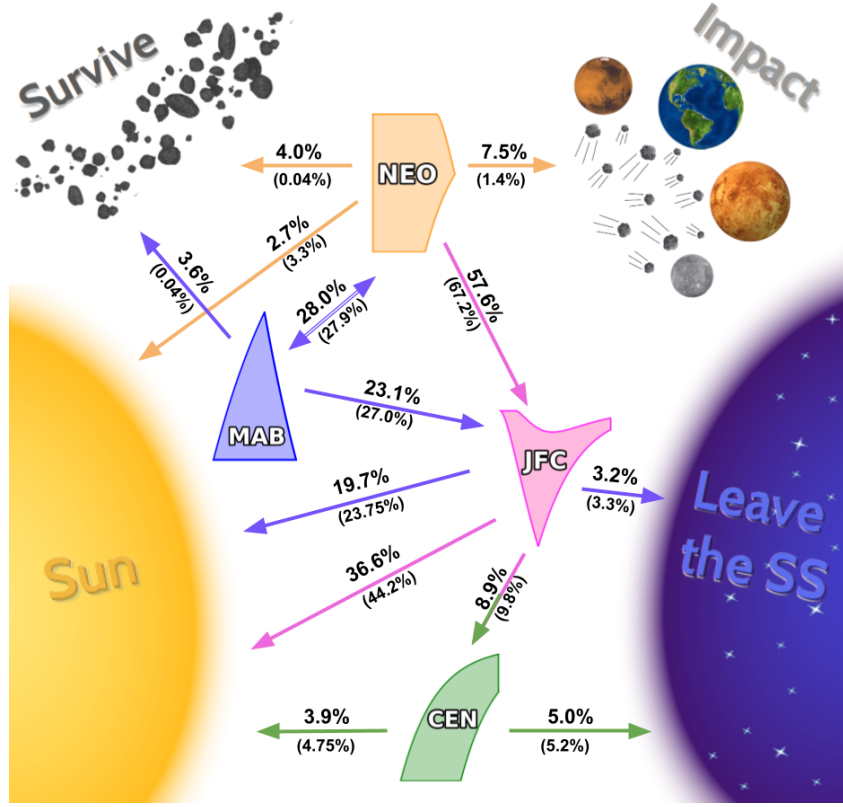


Figure 6: Main transference routes and fates for NEOs. The small rocks (top left) represent the surviving objects, the objects moving towards the planets (top right) indicate that the fate is a collision with a terrestrial planet, the yellow circle (bottom left) represent the fate of bodies that are destroyed by thermal disruption, and the blue circle (bottom right) the ejection from the Solar System. The routes are colour-coded, the orange arrows indicate the fates of “route Always NEO”, the blue arrows indicate the “route MAB”, the pink arrows are for “route JFC” and the green for “route CEN”. The numbers on the top of the arrows indicate the percentage of bodies that followed the transferences and fates from the initially NEO sample accounting for the thermal effects, and the values between parenthesis below the arrows are the weighted percentages in a steady state scenario, as discussed in Section 6.

maining bodies that take this route can either survive until the end of the simulation or take a Sun-grazing orbit that leads them to disruption in very close probabilities. Bodies that collided have a half-life time of about 32 Myrs, which shows that they were under resonant effects and therefore would have had much longer lifetimes if it was not for the unlucky collision with a planet. The large ratio of survivors among the bodies that take this route increases the estimated median lifetimes of the objects in this route to about 44 million years.

- **Route JFC** : This is the most common route a NEO can take. Almost 60% of the bodies that leave the NEO region go to the JFC region at first. Unlike the “Always NEO” route, these bodies are either ejected from the Solar System or hit the Sun, where the probability of ejection is about 5 times larger. The transference of bodies from NEO to JFC takes a median time of 3 Myrs and the median residence time of these bodies inside the JFC region is around 1.5×10^5 years, which means that most of the bodies transferred to this region are driven to low pericenter orbits

very fast. Even though it is not in the scope of this work to compare the transferred objects with current populations, we do point out that this median dynamical lifetime is in agreement with those found in other works [12; 29], which is an interesting sign that these objects may have evolved into cometary orbits and thus may have become members of the Jupiter family comets for some time.

- **Route MAB** : Almost 30% of the sample is primarily transferred to the Main Asteroid Belt, but almost all these bodies are transferred back to NEO right after. We found that the NEO-MAB exchange happens several times before about 80% of these bodies reach the JFC region and then get driven to orbits passing near the Sun. Due to the many resonances discussed in Sec. 5, MAB seems to be a transitional region for the bodies in our sample of study, because most of them do not end their lives while still inside of it. The first transference from NEO to MAB takes a median time of 1.5 million years, and they have a median residence time of 0.5 Myr inside this region. This is the region (besides NEO) in which

bodies tend to spend more time, probably due to resonances that hold the objects in the inner Solar System for longer periods and the small probability of close encounters with planets.

- **Route CEN** : We find that almost 10% of the sample, after spending some time in the JFC, reaches the CEN region. As expected, that is the route where the objects are more likely ejected from the Solar System than hit the Sun, unlike the other routes, but there is a similar probability of hitting the Sun. We find that these bodies take a median time of about 3 million years to reach CEN coming from NEO and passing through the JFC region. They spend approximately 100 thousand years as median residence time inside this region, but almost 2 Myrs on average, which is comparable to the estimated dynamical lifetime of centaurs in the order of 10^7 years[30; 46; 9]. Most of the bodies that reach this region are eliminated fast, while the rest stay for a considerable time. So it is not only possible but considerably likely that some of the bodies we find orbiting among the giant planets were once NEO.

5.3 The End of the Road

% of bodies per region	Survived	Sun-grazing	Ejected	Collision w/ Planets
NEO - 18.8%	7.4%	3.1%	0.0%	8.3%
MAB - 0.5%	0.5%	0.0%	0.0%	0.0%
JFC - 76.9%	0.1%	66.5%	10.2%	0.1%
CEN - 3.8%	0.0%	0.8%	3.0%	0.0%

Table 3: Percentage of bodies from our initially NEO sample in each region at the end of their lives, and their fates.

We studied the first steps and transferences to different regions of the filtered NEO population, but it is also interesting to analyse the last residence region before reaching their final fates. Table 3 shows the percentage of bodies in each region and their fate at the end of their lives. We see that more than 70% of the studied bodies end their life in the solar system while inside the JFC region, so we can say that this seems to be the “Highway to Hell” for NEOs. The strong perturbations from Jupiter and the MMRs in this region tend to significantly increase the bodies' eccentricities to 1, leading them to either leave the Solar System or go too close to the Sun to be destroyed by the thermal disruption.

We also highlight that, as exhibited previously in Table 2, at least 35% of the NEO population moved to the MAB region at some point, but less

than 1% is there at the end of their lives. It shows that MAB is a region where objects frequently pass through in the continuous exchange with the NEO region.

Additionally, the CEN region holds almost 4% of the bodies before they are ejected. So, as suggested at the beginning of this work, we confirm that some NEOs can take roads that transport them much further in the Solar System before they are eliminated, and there might exist centaurs today that were a NEO in the past.

5.4 NEOs Initially Inside JFC Region

The classical classification between asteroid and comet is made when the characteristics of the objects lie inside the usual dynamical parameters and physical properties defined for each group. The most usual way to differentiate comets from asteroids is to analyse if the object has icy or rocky composition and use the aforementioned Tisserand parameter to dynamically constrain the classification. However, a part of these bodies present orbital characteristics in which such simple classification does not work and therefore some additional analysis is necessary [13; 45; 14].

Although such an approach is useful for “instantaneous” classification, it might not work for much longer time scales as the dynamical evolution of these bodies inside the Solar System after millions of years might be chaotic enough to make them switch from one region to another. The objects in between both regions lie in similar regions of the phase space as the JFC region [45]. Therefore, it seems reasonable in our statistical study to assume the well-accepted concept that bodies with $2 \leq T \leq 3$ are inside the JFC region.

Region	%	Fate	%
NEO	71.5	Survive	0.7
MAB	6.3	Ejection	38.2
CEN	6.3	Sun-grazing	59.0
Remain	15.9	Collide w/ Planet	2.1

Table 4: On the left, the percentage of bodies initially inside the JFC region that were transferred to another region and those that remain inside the JFC region during its entire lifetime. On the right, the percentage of fates for the bodies initially inside the JFC region.

In our sample of objects, there were 144 bodies (14.62% of the total sample) initially in this condition and they were separately studied because due to the strong influence from Jupiter on their orbits, the results of the initially NEO population

could get biased. The results are summarised in Table 4, where it is shown the percentage of first transferences of the initially JFC objects to other regions, the percentage of those that remained inside JFC their whole lives and the rate of fates for this population.

We found that, from the 144 bodies initially inside the JFC region, more than 70% of them will be transported to the NEO region. Furthermore, almost 16% of this group remains inside the JFC region during their entire lives. It is a much larger percentage of objects that remain than those that were transferred to MAB or CEN regions. It is interesting to note that, even though we pointed out that the JFC region is the main exit of NEOs from the Solar System, as proven by the higher rate of ejection when compared to the initially NEO sample, these objects still are first transferred to the NEO region.

It probably means that, from what we learned to this point, the objects that remained inside JFC would be at the end of their lives and ready to leave the Solar System or hit the Sun. Those that were transferred to NEO are part of the objects that participate in the exchange between NEO-JFC, as shown in Table 2, hence at the beginning of their lives. It explains the high transference rate to the NEO region and also clarifies the lack of survivors and collisions with planets.

We can conclude then that these objects are part of the NEO population and follow similar behaviours, but separating them is indeed a good option because this population is dynamically biased and strongly affected by Jupiter, but reiterating that the objects in the JFC region we delimited are not necessarily classified as Jupiter-family comets.

6 Steady state

In this work, we presented the percentage of fates and routes for today's debiased large NEO population. The region is frequently fed by objects from the main belt, coming mainly from the ν_6 , 3:1J and 5:2J. However, the current large NEO population is believed to be in a near-steady state [18; 20; 21; 4], which means that there should be a balance between the flux of objects that enter the region and become NEO and the objects that leave the region [47].

The steady state refers not only to the number of objects in the population but also to their distribution in the region and their orbital characteristics. Therefore, in a rough and raw first analysis, there must be a nearly constant replacement of objects with similar orbital configurations. Of course, in the context of a population, things are not so linear and obvious, but that is

the concept of maintaining a steady state in number and orbital distribution.

Moreover, the timescales also should be consistent. Looking at the current population for 100 million years we see that 50% of the objects perish in less than 10 Million years, which means that this is the timescale in which half of the population dies and is replaced. Likewise, if an object in a particular configuration is lost in 1 million years, likely, objects in very similar configurations will also die in the same timescale. So this particular object would be replaced 100 times over the period we are studying, whilst the objects that survived would not have been replaced yet.

Therefore, we apply this simple approach to fit our results consistently to a steady-state configuration over 100 million years. For each object lost we assumed it was replaced by an identical body in the same initial configuration as the one that was lost, so we could weigh our results. Table 5 shows the percentage of fates weighted by the number of objects when assuming a steady state, and for the case with and without thermal disruption, only for the objects initially inside the NEO region. Also, it gives the total number of objects in the population throughout the 100 million years.

	% Weighted	
	$q < R_\odot$	$q < 0.058 \text{ au}$
Survivor	0.2%	0.1%
Collision w/ Planets	3.6%	1.5%
Ejection	58.5%	13.3%
Sun-grazing	37.7%	85.1%
Total number of objects	41841	82636

Table 5: Weighted percentage of fates and a total number of objects when considering a steady-state with constant feeding of objects in the region. These results take into account only the objects initially inside the NEO region. Column " $q < R_\odot$ " represents the data from the analysis considering that the limit assumed for an object that hits the Sun is if it has a pericenter smaller than the Sun radius, and the column " $q < 0.058 \text{ au}$ " represents the results when the limit is the minimum distance for thermal disruption for km-size objects.

At first, we notice that the number of objects is a couple of orders of magnitude larger than the population assumed to be in the steady state, which is expected as was mentioned before that these objects are constantly leaving the region and being replaced. Also, we notice that there is no significant difference between the fractions of collision and survivors in the different scenarios.

It makes sense since most of these objects usu-

ally do not suffer strong perturbations during their lives and have orbits in a less chaotic vicinity [37; 35; 17; 16]. However, the objects that go towards the Sun or out of the Solar System are highly perturbed and the rate of fates change considerably from one case to another. When considering the thermal disruption we have 85% of the sample being destroyed, whereas in the case without thermal disruption this number is half, and close to the number of ejections as discussed in the previous section.

It means that 40% of the objects that would be ejected could have been destroyed in less time due to the heat from the Sun. For that reason, the total number of bodies in the case with thermal disruption is almost double the number of objects in the case without it.

Granvik et al. (2018) [20] study the debiased NEO population of 100 m-sized asteroids in a steady state and present results for the rate of fates in four different scenarios, with and without thermal effects. The values presented in Table 3 of [20] for collision with the Sun in the scenarios with thermal disruption are almost all zero, and the authors do not show explicitly which are the rates of objects destroyed by the thermal disruption.

Since there should be a very small number of survivors, and the percentages of these cases do not add to 100%, we assume that the missing percentages are related to the thermally destroyed objects. The authors show that the main source of NEOs from the main belt is the ν_6 complex, which presents a rate of collisions with planets between 3% and 9%, ejections between 13% and 15% and collisions with the Sun between 75% and 83%, for the case without thermal disruption.

For the case with the km-size thermal disruption limit, they find collisions between 2% and 8%, ejections between 12% and 14%, and thermal disruption between 78% and 85%. It seems that there is no significant difference between both scenarios presented by [20], which is not explained by the authors, but we believe it could be either due to the small size of the objects that were proven to have smaller lifetimes than km-size NEOs or because the model they used assumed a distance for collision with the Sun close to the thermal disruption limit. In any case, the rates of fates found with the thermal effect corrections are in agreement with the values we find for the cases with the same considerations.

Furthermore, the fate rates and total population numbers are linked to the timescale chosen. In 100 million years the number of survivors is small and most of the objects would have been replaced several times. Considering

smaller timescales, a larger part of the population survives. For instance, the half-life time of the population is around 5-10 million years depending on the considerations, as discussed before.

In this case, 50% of the population survives and the total number of objects in the population would be much smaller. Yet, if we tend to infinite time we will find that there are no survivors and the ratio of collisions is negligible. While Sun-grazing and ejections, for the case with and without thermal disruption respectively, would represent almost all the fates.

Therefore, we can say that even though the population is constantly changing because of the flux of objects, since it is in a nearly steady state the objects should have similar evolution, following the same routes and ending in nearly the same fates as the current known population, as shown in Table 2 where the values in parenthesis represent the percentage of the steady-state population that followed each route.

7 Final Comments

Our work aims were to revisit the dynamical evolution of the large known NEO population and bring new results using recent data with a more significant number of objects.

From the km-size objects sample studied, 13% of them are ejected from the Solar System, which represents a considerable interstellar contribution from the large known NEO population.

Also, 70% of the objects are driven to low pericenter orbits where the solar thermal effects cause their demise. Therefore, thermal disruption is the most efficient mechanism to eliminate objects initially inside the NEO region.

We have shown that about 14% of the objects never leave the NEO region (Always NEO), which is a considerable amount of bodies. From those, about 1/3 survive because they are under Jupiter's secular perturbation effects that maintain them confined inside the NEO region in a location where they are more protected from resonances and the high inclinations protect them from close encounters with the planets.

Additionally, we point out that the usual division of NEOs (Atira, Atena, Apolo and Amor) does not seem to make much sense to classify these bodies in longer timescales because they wander among these classes frequently during their lives.

Furthermore, we have shown that the JFC is the preferable region for NEOs, at first and at last. Almost 60% of the sample is firstly transferred to the JFC region, and 77% end their lives while still inside of it, at a ratio of approximately

5 Sun-grazing objects to each ejection from the Solar System.

Moreover, MAB is a region for frequent transferences with a massive exchange of bodies with the NEO region. From the approximately 35% of bodies that eventually reach the MAB region, only 0.5% stay inside it until the end of their lives. But, even though MAB is a transitional region for most objects, it is the second region most favourable for survivors.

It is important to highlight that almost 10% of the studied sample can reach the CEN region, and some can remain there for a considerable time, which suggests that some objects present in this region today could have been NEOs before.

Finally, the work shows that close encounters with the terrestrial planets or Jupiter, and resonances with these planets, will define each one of the routes encountered. There is no single dominant mechanism, but a combination of effects in each outcome.

Acknowledgements

This research was supported by resources supplied by the Center for Scientific Computing (NCC/GridUNESP) of the São Paulo State University (UNESP). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, also by CAPES-PRINT Process 88887.570251/2020-00, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - Process 305210/2018-1, and by FAPESP Process 2016/24561-0. Thanks to Tais Ribeiro for her help with preliminary cartoons, and thanks also to Gonzalo Tancredi for the important comments and suggestions.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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3.3 On the Orbital Inclination Evolution of the Current Large NEOs

On the Orbital Inclination Evolution of the Current Large NEOs

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Abstract

This work aims to discuss the temporal evolution of the current large NEOs' orbital inclination. We applied a numerical integration method to solve the N-body gravitational problem. We used Mercury's hybrid symplectic/Bulirsch-Stoer algorithm to perform the integrations, covering a period of 100 million years, for a sample of **985** current large NEOs, the Sun, and the eight planets of the solar system. We found that the NEOs with initially low inclinations tend to significantly and rapidly increase their orbital inclinations. We also identified an intermediate range of inclinations between $\sim 20^\circ$ to 60° where the objects tend to be less perturbed, which is favourable for the long-lived NEOs. We also found that the NEOs with very high initial inclinations are lost more quickly unless they are brought into the intermediate range by decreasing their orbital inclination. The results of this study provide new insights into the current distribution of NEOs orbital inclinations. Overall, we have shown that the evolution through the terrestrial planets region effectively changes the NEOs' orbital inclination, often through a gradual accumulation. The changes result from a combination of typical perturbations in this region and may impact various aspects of the minor bodies' orbital evolution, such as their lifespans and fates.

Keywords: NEOs, orbital inclination, asteroids

1 Introduction

The population of minor bodies in the solar system is composed of small objects that orbit the Sun but are not considered planets. Examples of minor bodies are asteroids, comets, and meteoroids.

Various regions within the solar system contain asteroid populations, some more prominent than others. The main asteroid belt (MAB) is the most significant concentration, situated between the orbits of Mars and Jupiter. The estimation is

that there are 1.1–1.9 million 1 km-sized asteroids within the belt.

Asteroids are considered to be remnants of the formation of our solar system. As a result, they likely maintained a configuration with low eccentricity and orbital inclination, meaning that their orbits were nearly circular and aligned with the ecliptic plane. [1].

Some objects in the main asteroid belt may have undergone orbital changes, resulting in their

current eccentric and inclined orbits [1–3]. However, most MABs present an orbital inclination of less than 20° [4].

Another interesting group of minor bodies is the NEO (Near-Earth Objects), which include asteroids, meteoroids, and comets. They can approach and even cross the orbits of the terrestrial planets. According to a formal definition, NEOs are celestial objects that orbit the Sun within a perihelion distance of $q \leq 1.3$ au [5]. These objects can be further classified as NEAs (Near-Earth Asteroids) or NECs (Near-Earth Comets). Updated numbers from JPL NASA show that NEAs correspond to $\sim 99.6\%$ of the NEOs' population.

According to Gladman et al. [6], the dynamical lifetime of a NEO is approximately 10 million years, which is a relatively short time when compared to the age of our solar system. It suggests that the NEO population must be replenished over time, under a steady state assumption [7].

Studies have shown that MAB is the primary source of NEOs. The mean motion and secular resonances [8, 9], enhanced by non-gravitational perturbations such as the Yarkovsky effect [10–12], create a regular transport of objects from the main-belt to the NEOs region.

According to Morbidelli et al. [13], asteroids in the main belt are primarily affected by the 3:1 mean motion resonance with Jupiter and by the secular resonance ν_6 with Saturn. These perturbations induce orbital eccentricity excitation. As a result, the asteroids with eccentric orbits become Mars-crossing asteroids (MCAs) and may occasionally enter into the region of terrestrial planets.

A recent study by Liberato, Araujo and Winter [14] investigated the dynamical evolution of the large known Near-Earth Objects (NEOs). The study identified preferential routes for NEOs, which include transfers to Jupiter Family Comets (JFCs) and Centaurs regions and frequent exchange of bodies between NEO and Main Asteroid Belt (MAB) regions. The study also discussed the implications of this evolution on the determination of NEOs' lifetime and fates. However, the authors did not analyze the evolution of the object's orbital inclination.

As a complementary study to the one made by Liberato, Araujo and Winter [14], in the present work, we aim to investigate the orbital inclination

evolution of the large objects currently classified as NEOs on their headway in the solar system. The sample size included 985 known large NEOs with an estimated diameter of at least 1 kilometer. These NEOs represent a steady-state population free of observational bias, as most large NEOs are already known [15].

The paper is structured as follows: Section 2 outlines the initial conditions and methodology used, while Section 3 presents the results. Finally, Section 4 provides our final remarks and an overview of the major findings of our work.

2 Methodology

As a follow-up study, in this work we use the same simulations from [14]. To investigate the gravitational perturbations suffered by the known large NEO population, the authors considered a system consisting of the Sun, the 8 solar system's planets, and a group of 985 of known NEOs with an estimated diameter of at least 1 km.

The NEOs' orbital elements used as initial conditions were obtained from the ESA NEO database ¹ [16], while the planets' orbital elements were obtained from JPL's Horizons system, all at the same epoch.

The authors used the adaptive time step hybrid symplectic/Bulirsch-Stoer algorithm implemented in MERCURY package [17] to perform a set of numerical integrations of the N-body gravitational problem equations [18] for a period of 100 million years. The output step was set at 2.5 years, with an algorithm changeover of 3 Hill's radii and a base time step of 2 days.

The NEOs are treated as massless particles in the simulations, where they are affected by the gravitational perturbations from the massive bodies (the Sun and the planets) but cannot disturb each other or the massive bodies. The objects can either collide with the massive bodies or be ejected when evolving to a hyperbolic orbit. The collisions are determined by the physical size of the planets and the Sun. Additionally, the perihelion distances of the NEOs' orbits are calculated for each output step. If the perihelion distance of a NEO is smaller than the Sun's radius, it is deemed as a Sun-grazer and removed from the simulation.

¹<https://neo.ssa.esa.int/>

To analyze the evolution of the large current NEOs' orbital inclination, we generate output files that show how this element changed over time at each 2.5-year output step. Our study relies on a statistical analysis of the entire sample's evolution.

3 Results

Figure 1(a) shows the initial distribution of orbital inclination for the 985 studied NEOs. Initially, there is a concentration of objects with $i \lesssim 50^\circ$, with a median at $\sim 21^\circ$ and a maximum distribution in $8^\circ - 10^\circ$, and only one retrograde NEO with $i = 154.3^\circ$.

Meanwhile, Figure 1(b) shows the final inclination distribution computed using the last registered inclination for each NEO. Notice that the median shifted to $\sim 36^\circ$.

Comparing the initial and final inclination distributions shown in Figure 1(a) and Figure 1(b), respectively, it becomes clear that the NEOs region has caused a significant increase in the object's median orbital inclination. The median inclination of the sample at the end of the objects' lives is approximately 1.7 times greater than at the start of the simulations, which is also seen with the dispersion in the data. The initial inclinations, which had values concentrated below $\sim 50^\circ$, show at the end a spread distribution that reaches orbital inclination values of around 170° .

Results in Figure 1(b) also indicate that a considerable amount of NEOs have attained a retrograde orbit ($i > 90^\circ$). We find that 109 NEOs ($\sim 11\%$) ended their lives while in a retrograde orbit, excluding the only initially retrograde object. On average, it takes around 15 million years for an initially prograde NEO to evolve into a retrograde orbit.

Figures 1(c) and 1(d) show, respectively, the relative and absolute total orbital inclination variation computed as the difference between the last recorded inclination value relative to the initial inclination for each studied NEO.

Figure 1(c) shows the data concentration falling within a range of approximately $\pm 20^\circ$. However, the uneven distribution around $i = 0^\circ$ suggests a preference for final positive variations, meaning a trend towards increasing the final orbital inclination values. The primary cause for this asymmetry might be the geometry of close

encounters, which can be advantageous or disadvantageous for increasing the orbital inclination [19, 20].

In Figure 1(d), there is a noticeable cluster of absolute variations in inclination around 20° . The median for this distribution was calculated to be 16.7° , indicating that more than half of the sample experienced a change in initial orbital inclination of over 15° during their temporal evolution. Additionally, approximately 17% of NEOs in the sample suffered a variation in inclination greater than 50° . The maximum absolute variation recorded was 161.5° , occurring after roughly 1 million years of evolution. A more detailed discussion about this extreme case will be presented in Section 3.1.

Figures 1(e) and 1(f) show the relative and absolute distributions of the maximum variation of orbital inclination for each NEO within a one-time step period. Notice that the results in Figure 1(e) present a nearly symmetrical behaviour, indicating that the studied objects have an almost equal chance of increasing or decreasing their inclination values in a relatively short time. The extreme variations, higher than 50° , can be quickly reached, likely due to a single event such as a close planetary encounter. However, such events are not very common. Figure 1(e) shows a Gaussian-like distribution with the median around zero and a standard deviation $\sigma \approx 24.5^\circ$, which reveals that typical perturbations within the NEO region are more likely to cause minor to moderate variations in the object's orbital inclination.

The median of the distribution shown in Figure 1(f), found to be at 11.5° , means that over half of the sample experienced a change of less than 12° in their initial orbital inclination within a single time step. Therefore, these findings suggest that large variations in orbital inclination are most likely the result of a cumulative process over time rather than an isolated event.

The initial and final distribution in the $(a \times e)$ space of the 985 known large NEOs and the final state of the orbital inclination at these two moments are shown in Figures 1(g) and 1(h), respectively.

Figure 1(g) shows that the net effect of the variation of the orbital inclination does not significantly depend on the initial conditions in the $(a \times e)$ space.

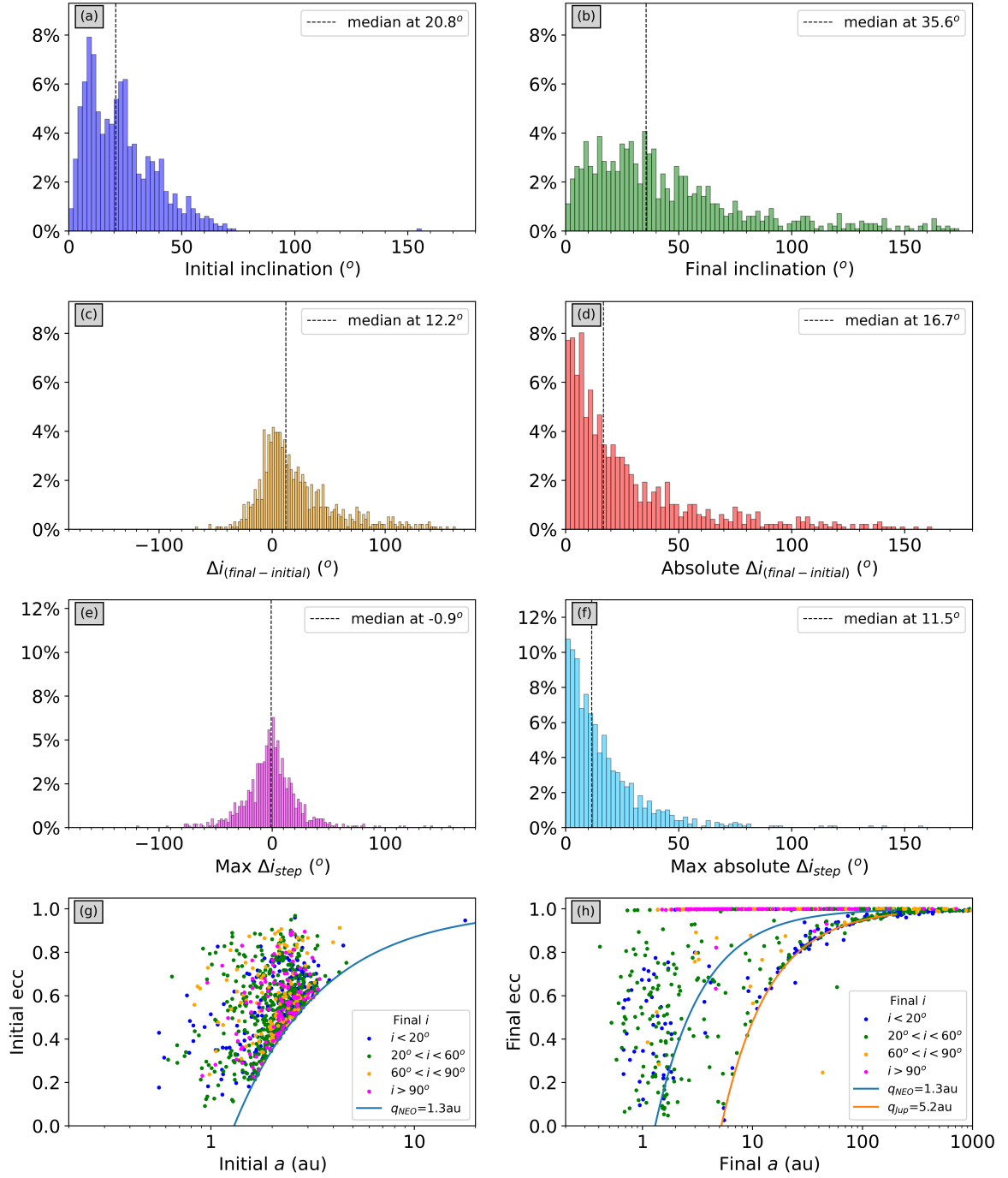


Fig. 1 a) Initial distribution ($t = 0$) of orbital inclinations of the sample 985 of NEOs. b) Final distribution of orbital inclinations. c) Distribution of relative variation in orbital inclination ($i_{\text{initial}} - i_{\text{final}}$). d) Distribution of absolute variation in orbital inclination ($|i_{\text{initial}} - i_{\text{final}}|$). e) Distribution of maximum variation in orbital inclination recorded within two output steps (2.5 years). f) Distribution of absolute maximum variation in orbital inclination recorded between two output steps (2.5 years). All percentages are relative to the entire sample of 985 NEOs. Vertical dashed lines indicate the median values and each vertical bin is equal to 2° . g) Initial distribution in the ($a \times e$) space and the final state of the orbital inclination (i), for the 985 NEOs. h) Final distribution in the ($a \times e$) space and the final state of the orbital inclination (i) and the, for the 985 NEOs. The term “final” refers to the last registered data for each NEO.

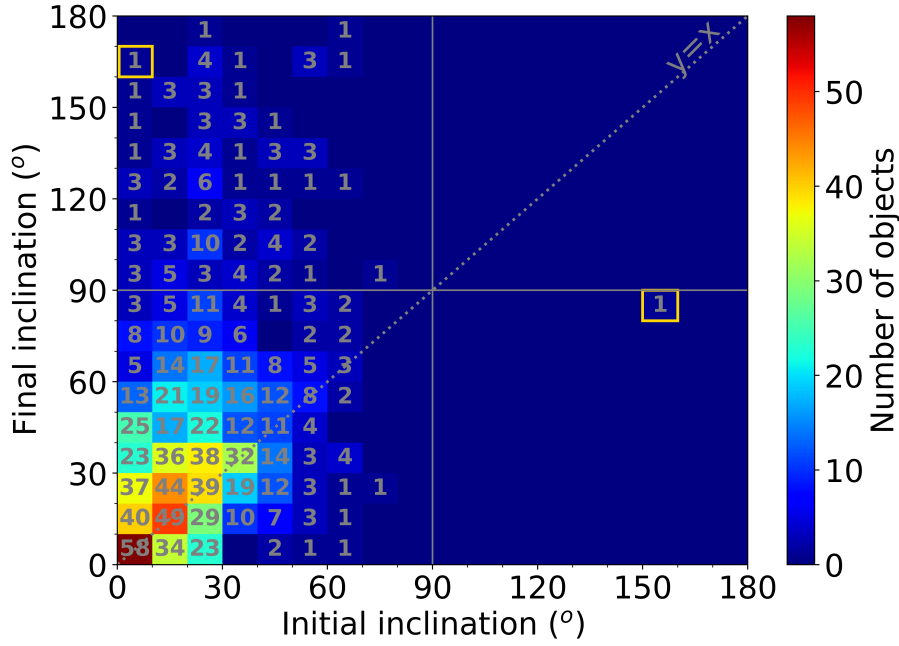


Fig. 2 The number of NEOs as a function of their initial and final orbital inclination. The diagonal grey dotted line marks the point where $i_{\text{initial}} = i_{\text{final}}$. The yellow contoured squares highlight two cases of interest. The horizontal and vertical bins are both 10° . The number of objects in each vertical bin is 226 ($0^\circ - 10^\circ$), 246 ($10^\circ - 20^\circ$), 243 ($20^\circ - 30^\circ$), 126 ($30^\circ - 40^\circ$), 80 ($40^\circ - 50^\circ$), 42 ($50^\circ - 60^\circ$), 19 ($60^\circ - 70^\circ$), 02 ($70^\circ - 80^\circ$) and 01 ($150^\circ - 160^\circ$), respectively.

Fig. 1(h) shows that some NEOs end up outside the NEOs' region after completing their journey through the solar system. Such behavior is detailed in a study by Liberato et al. [14]. The authors discuss the intricate dynamics that govern the orbital evolution of the current large NEO population as they travel among other regions in space, including the JFC, Centaurs, and MAB.

Figure 2 shows the variation in the number of bodies with respect to their initial and final orbital inclinations (the last values recorded for each NEO in the sample). The value and the colour in each square represent the number of objects that started the simulation within the 10-degree interval shown in the x-axis and ended within the 10-degree range shown in the y-axis. The grey diagonal line indicates where the initial inclination is the same as the final inclination. Below this line, we find the cases where the final inclination is lower than the initial value, while above the line are the cases where the final inclination is higher than the initial one. From the data presented in this diagram, it is clear that the studied NEOs are more likely to experience an overall

increase in their final orbital inclination than a decrease.

From Figure 2, we notice that objects from all ranges of initial inclinations could evolve to a retrograde orbit, suggesting that no specific range of initial inclination favouring the development of NEOs into retrograde objects. The NEOs that achieved the most significant variations are those with an initial inclination of $0^\circ \leq i \leq 10^\circ$ (first vertical bin in the grid) who were able to achieve final orbital inclinations of more than 150° .

We can gather interesting information from the vertical bins in Figure 2. For NEOs with an initial inclination of $0^\circ \leq i \leq 10^\circ$, about 26% finished the simulation with almost no change in inclination. Additionally, 18% finished with an inclination of $10^\circ < i \leq 20^\circ$, meaning their orbital inclination was duplicated. Furthermore, 16% had their initial orbital inclination triplicated, while 10% had it quadrupled, and so on. However, for bodies with an initial inclination of $40^\circ \leq i \leq 50^\circ$, only about 4% and 5% had their inclination doubled or triplicated, respectively, over time. It shows that many of the studied NEOs that start the simulation with low-inclined orbits are prone to experience

a significant increase in their orbital inclination. Meanwhile, the likelihood and extent of such an increase are considerably lower for objects with initially highly inclined orbits.

3.1 Two particular cases

The yellow squares in Figure 2 showcase two interesting scenarios. The first pertains to an extreme case where one of the studied NEOs started the simulation with low inclination and ended in a retrograde orbit with an inclination of 169.7° . The second one highlights the case of an initially retrograde object that finished in a prograde orbit. Figs. 3 and 4 display the temporal evolution in semi-major axis, eccentricity, and orbital inclination for both cases.

The first example is presented in Figure 3(a). It shows the orbit of an object that started the simulation with an inclination of 8.2° , a semi-major axis of 2.1 au, and an eccentricity of 0.4. It collided with the Sun after approximately 1 million years. The inclination and semi-major axis remained relatively stable for about 0.8 million years, while the eccentricity doubled in the same period. The remaining 0.2 million years show significant orbit changes. Figure 3(b) shows a closer look at the time interval between 0.75 – 1.00 million years, where we can see the object's chaotic evolution, similar to a planet-crossing orbit [21, 22]. The close encounter with a planet typically causes such evolution, evident from the "jumps" in the graph displaying the studied NEO's semi-major axis over time.

Furthermore, we notice the orbital inclination and eccentricity oscillating for a significant period of time in Figure 3(b). During the time intervals of 0.80 – 0.85 and 0.92 – 0.95 million years, the apparent coupling between those elements suggest the influence of the Kozai-Lidov mechanism [23, 24].

The zoomed-in plot in Figure 3(c) displays the orbital evolution in the last 6,000 years for the given example. It highlights the intricate chaotic dynamics of the large NEOs, where various perturbations compete, resulting in an unpredictable final state.

The second interesting case presented in Figure 4(a) shows the variations in the orbital elements of one of the studied NEOs that initially had an inclination of 154.3° , semi-major axis of

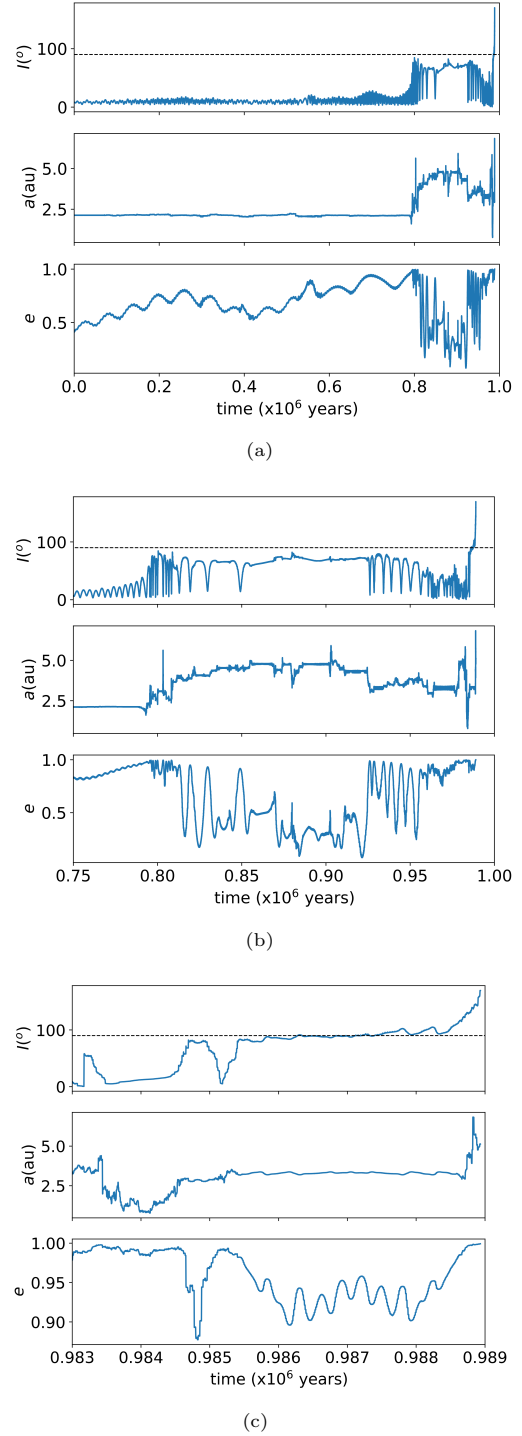


Fig. 3 Temporal evolution of the inclination, semi-major axis and eccentricity of a low-inclined NEO with initial values of $i = 8.2^\circ$, $a = 2.1$ au and $e = 0.4$, and that reached a retrograde orbit ($i = 169.7^\circ$). a) The entire time interval that the NEO remained within the system. b) A zoom showing the evolution within 0.75 – 1.00 Myr. c) A zoom showing the evolution within the last $\sim 6,000$ years previously to the collision of the NEO with the Sun.

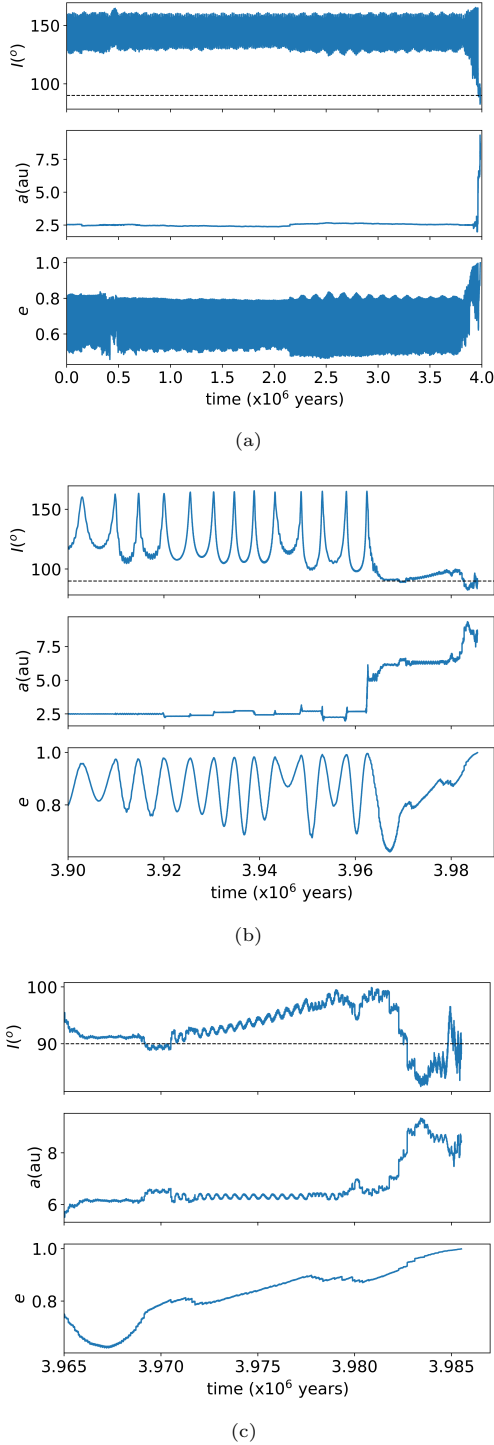


Fig. 4 Temporal evolution of the inclination, semi-major axis and eccentricity of a NEO with initial retrograde, with initial values of $i = 154.3^\circ$, $a = 2.5$ au and $e = 0.8$, and that reached a prograde orbit ($i = 88.3^\circ$). a) The entire time interval that the NEO remained within the system. b) A *zoom* showing the last ~100,000 years of evolution. c) A *zoom* showing the evolution within the last ~35,000 years previously to the ejection from the system.

2.5 au and eccentricity of 0.8. It was ejected after around four million years, with a last recorded inclination of 88.3° . In this case, the orbital elements were not significantly changed for about 3.9 million years. During this time, the semi-major axis remained almost constant. The eccentricity, however, oscillated between 0.5 and 0.8, whereas the inclination oscillated between 130° and 160° .

Figure 4(b) helps visualize the inclination and eccentricity oscillatory behaviour. Such behaviour is likely a result of the action of secular resonances since the coupling between these elements is unclear. From around 3.92 million years, there is a noticeable variation in the semi-major axis due to close encounters. Since these encounters dominate the large NEO's dynamical evolution, the values of a , e , and i become unpredictable.

Minor celestial bodies that enter the terrestrial planets region experience various perturbations apart from gravitational interaction during a close encounter with a planet, such as the effects of secular resonances [25–28] and Kozai-Lidov secular perturbations [23, 24]. These perturbations lead the orbital inclination and eccentricity into an oscillatory state. In some cases, the variation of these two orbital elements is coupled, i.e., the maximum value of orbital inclination corresponds to the minimum value of the orbital eccentricity and vice-versa. This behaviour is typical of bodies affected by the Kozai-Lidov mechanism. This mechanism states that bodies with inclination values near the Kozai cycle interval ($39.2^\circ \leq i \leq 141^\circ$) experience oscillations in their e and i values such that the Kozai-Lidov parameter given by $\sqrt{1 - e^2} \cos(i)$ remains constant. Previous works have shown that asteroids, including the NEOs, can be influenced by Kozai-Lidov [29]. In fact, studies show that this mechanism helps ensure the long-term stability of NEOs by preventing them from having close encounters with planets [30].

The discussions for the two cases presented show that the changes in orbital elements, especially in inclination, are more likely the outcome of a combination of external disturbances than caused by a single event. Due to the chaotic nature of the orbital evolution of NEOs, we do not analyze each case separately. Instead, we focus on the statistical analysis of the studied sample altogether.

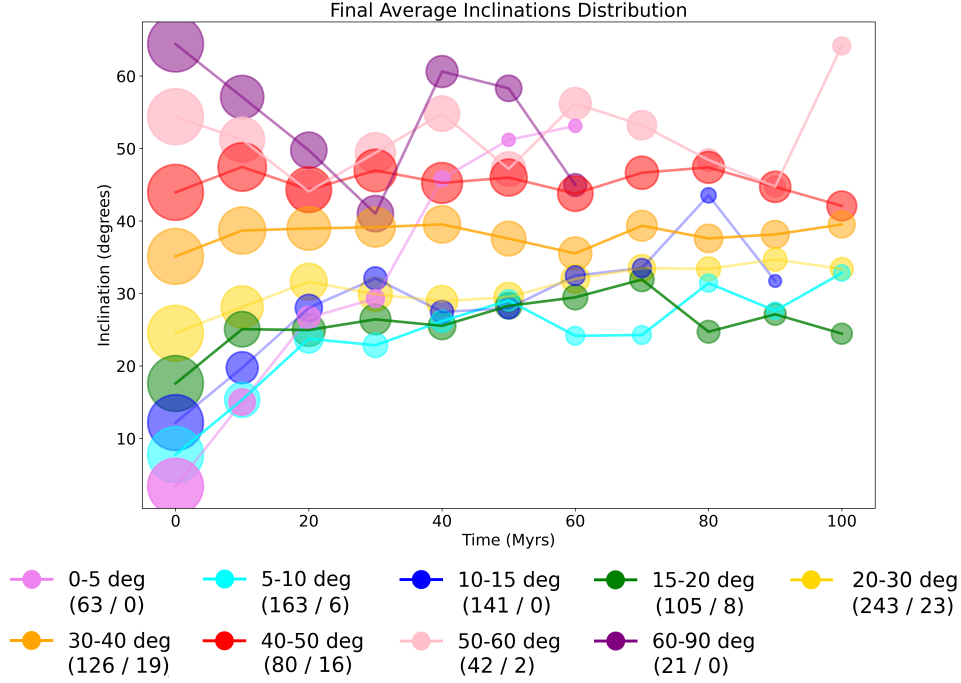


Fig. 5 Temporal evolution of the average inclination as a function of the initial inclination. The initial inclinations ranging from 0° to 20° are separated in intervals of 5° . For initial inclinations between 20° and 60° , the intervals are taken every 10° , and between 60° and 90° all objects are taken in one interval. The size of the coloured circles indicates the fraction of remaining bodies at each time, with respect to the number of objects that started the simulation with inclinations within each range. Each circle at $t = 0$ contains a different portion of the total sample of studied NEOs but represents 100% of such portion. The colour code shows the range of inclinations, and the numbers in parentheses indicate the starting and ending numbers of NEOs within each range.

3.2 Temporal Evolution

In the previous sections, we analyzed the data shown in the histograms in Figure 1 and Figure 2, considering the net effect of the typical perturbations acting on objects in the NEOs' region. This section will discuss the temporal evolution of the studied objects' orbital inclination.

We sorted the group of 985 large current NEOs into different categories based on their initial orbital inclination. The inclination intervals ranged from 0° to 20° in increments of 5° , 20° to 60° in increments of 10° , and 60° to 90° . We calculated the average orbital inclination for each range of NEOs every 10 Myr. Please refer to Table 1 and Figure 5 for more information. In Figure 5, the size of the coloured circles is associated with the remaining number of bodies relative to the initial sample at each inclination range and period.

Figure 5 shows the results of the entire integration time (100 million years). We can notice that there is a trend toward increasing the average orbital inclination for those NEOs with low

initial inclination ($i \lesssim 20^\circ$). According to [31], encounters between planets and low-inclined bodies are more likely to occur than encounters with high-inclined bodies.

The data in Figure 5 also reveals an intermediate behaviour where there seems to be an interval where the average orbit experiences slight changes over time. Initial inclinations between approximately 20° and 60° apparently bounds the range of intermediate inclinations that favours objects' stability. It is also worth noting that the average orbital inclinations for low and high-inclined initial orbits converge to this same range. The NEOs with very high initial inclinations are lost more quickly unless they are brought into the intermediate range by decreasing their orbital inclination.

Large current NEOs with low orbital inclinations seem to be more disturbed and may undergo significant changes to their initial state. However, based on the data presented in Figure 2, it appears that, on average, objects with inclinations smaller

Table 1 Number of remaining objects at each 10 Myrs interval as a function of their initial inclination distribution.

Time (Myrs) \ Initial Inclination (deg)	0-5	5-10	10-15	15-20	20-30	30-40	40-50	50-60	60-90	>90
0	63	163	141	105	243	126	80	42	21	1
10	9	50	34	33	118	82	56	24	11	0
20	6	29	22	27	84	67	48	20	7	0
30	3	19	14	23	68	53	40	18	7	0
40	2	15	14	17	55	45	36	13	5	0
50	1	13	11	15	47	37	28	12	3	0
60	1	9	9	13	43	33	25	10	2	0
70	0	9	8	12	38	27	21	8	0	0
80	0	8	4	10	27	22	19	4	0	0
90	0	7	2	9	25	21	18	3	0	0
100	0	6	0	8	23	19	16	2	0	0

than 20° at the beginning of the simulation are not able to reach an inclination higher than 35° . We find that there is only one exception to this trend, where one of the studied NEOs with an initial inclination between 0° and 5° evolved into an orbit with an inclination of approximately 52° after about 60 million years of simulation.

3.3 Lifetime and fates

In this study, we found that NEOs with an orbital inclination exceeding 70° at the beginning of simulations, or those that eventually reach such values, do not survive for more than 6 Myr. Furthermore, we found that it takes an average of 15.2 Myr for prograde NEOs to evolve into a retrograde orbit, but their typical lifespan is approximately 15.6 Myr. It means that, on average, these objects usually remain in the system for only a few thousand years after becoming retrograde, showing their short-lived nature.

Figure 5 shows that the studied NEOs with low inclinations (less than 10°) show a significant increase in their orbital inclination. This increase can be attributed to external perturbations like close encounters with planets, which affect less inclined orbits the most [31]. Additionally, the same figure shows that NEOs with low-inclined orbits that survived for over 10 million years within the system had their average orbital inclination increased by more than 10° . The average lifetime of the 58 NEOs that started the simulation with an orbital inclination between 0° and

10° and remained within this range until the end of their lives is 4.4 million years.

The data in Table 1 indicate that NEOs with orbital inclinations ranging from $20^\circ - 60^\circ$ at the start of the simulation have a probability of $\sim 57\%$ of remaining in the system for a minimum of 10 million years. Additionally, there is a good chance they will stay in the system for at least 20 million years with a probability of $\sim 45\%$. The table further indicates that NEOs with orbital inclinations between $20^\circ - 60^\circ$ are more likely to stay within the system, with a probability of approximately 12% to reach a lifespan of 100 million years.

Understanding how the orbital inclination affects the lifespan of NEOs is crucial for research that focuses on their temporal evolution, such as the impact of space weathering on their surface or the formation and disruption of NEOs' binary systems.

The graphs in Figure 6 provide information about the fate of the NEOs based on their initial and final inclinations. NEOs can have one of four outcomes: colliding with the Sun or Sun-grazing, colliding with planets, getting ejected, or surviving. Figures 6(a), 6(c), and 6(e) indicate that there is no specific preferred initial orbital inclination for NEOs to leave the system.

The figures 6(b), 6(d), and 6(f) indicate that bodies with lower inclinations are more likely to collide with the planets, while those with higher inclinations are more likely to collide with the Sun.

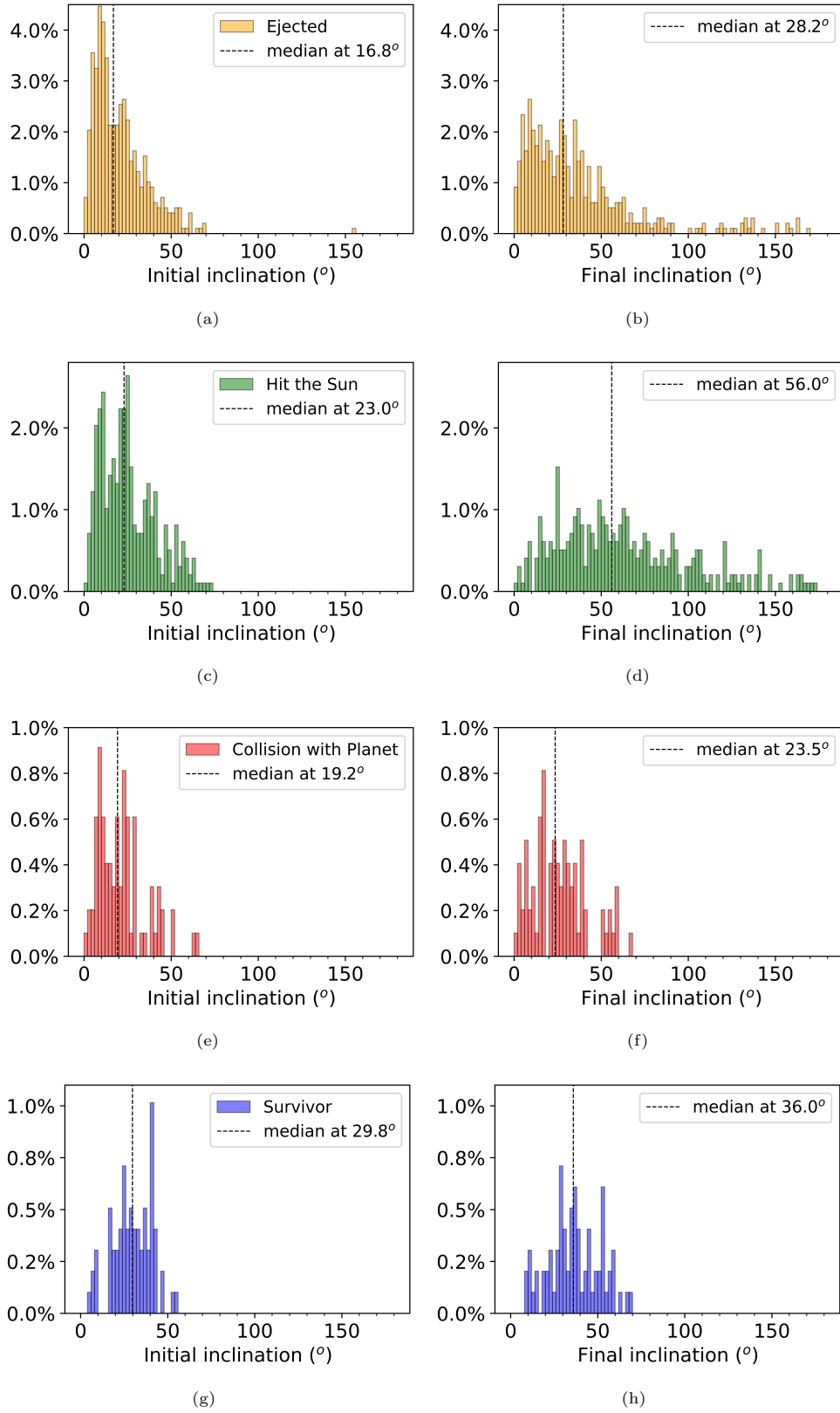


Fig. 6 Distributions of the studied NEOs' initial and final orbital inclinations separated by fate.

The graphs in Figures 6(g) and 6(h) support our previous discussion. They show a concentration of the surviving NEOs within the range of $20^\circ \lesssim i \lesssim 60^\circ$. These bodies are the ones that are most likely to remain within the system.

4 Final remarks and Conclusions

This study aimed to examine how the orbital inclination of current large NEOs changes due to perturbations experienced by these minor bodies.

Overall, we computed an increase in the median of the orbital inclination by ~ 1.7 times for the studied NEOs. The variations in inclination over the object's lifetime are mostly less than 20 degrees, but more significant variations are also possible. Out of the 985 large current NEOs we studied, around 17% experienced a variation of more than 50 degrees, and approximately 11% of the NEOs that initially had prograde orbits ended up with retrograde orbits.

A preference for positive variations has been observed, which means there is a trend towards an increase in orbital inclination in the long term. However, the studied NEOs presented almost an equal chance of increasing or decreasing their inclination in a relatively short time, and they are more likely to produce only a tiny relative variation. This indicates that large variations in orbital inclination at the end are most likely the result of a cumulative process over time rather than a sudden and extreme event.

After analyzing the temporal evolution of the orbital inclination, we face an interesting scenario. Current large NEOs with low inclinations tend to rapidly increase their initial orbital inclination, whereas high-inclined NEOs are more likely to leave the system in a short time if their inclination is not decreased. Thus, the variation in inclination appears to converge towards a range of $20^\circ \lesssim i \lesssim 60^\circ$.

Data from the MPC (Minor Planet Center) database explored by Zain et al. [32], show that about 56% of the NEOs with absolute magnitude $H < 16$, have orbital inclinations $i > 20^\circ$. It was also estimated that about 1%–2.5% of the steady-state NEOs population evolves in a retrograde orbit [33, 34].

Zain et al. [32] have shown that only a tiny percentage of high-inclined NEOs originate from high-inclination asteroids of the Main Asteroid Belt. Granvik et al. [34] have shown that the process of moving MAB asteroids into the NEO region, which involves the mean motion and secular resonances at the main belt, can also transport some initially low-inclined MABs into high-inclined NEOs. However, this mechanism can also act oppositely, i.e., it can decrease the orbital inclination of the MABs on their way to the region of the NEOs. Fernández and Helal [35] have computed that the transfer rate of large Main Belt Asteroids (MCAs) with diameters greater than 10 km into the NEO region is around 1 million years for low-inclined orbits and 10 million years for high-inclined orbits. Therefore, it is likely that the high-inclined orbits observed among the NEO population result from the dynamic evolution they experience in the NEO region.

In the present study, we found that highly-inclined objects ($i > 60^\circ$) and those in retrograde orbits ($i > 90^\circ$) are likely to leave the system soon, and their most probable fates are either ejection or collision with the Sun. The initially low-inclined NEOs (with an inclination of less than 5°) can survive only up to 4.4 million years within the system unless their inclination increases. These objects are more likely to collide with some planet. The bodies that have survived longer in the system started or reached an orbital inclination between 20° and 60° . These bodies have survived for more than 60 million years. Conversely, none of the studied NEOs with an initial inclination of less than 20° has lived for over 20 million years without an increase in inclination.

The NEOs are more likely to leave the Main Asteroid Belt and enter the NEOs' region in low-inclined orbits. We have found that these orbits are more easily influenced and susceptible to change and have shorter lifespans than inclined NEOs. Therefore, it is reasonable to assume that the low-inclined NEOs currently known are recent additions to the region of terrestrial planets.

In summary, we have shown that transit through the NEOs region is an effective mechanism to significantly alter the orbital inclination of these objects, usually through a gradual accumulation process. This change results from a combination of typical perturbations in this region

and may impact various aspects of the minor bodies' orbital evolution, such as their lifespans and fates.

Acknowledgments. This research was supported by resources supplied by the Center for Scientific Computing (NCC/GridUNESP) of the São Paulo State University (UNESP). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, also by CAPES-PRINT Process 88887.570251/2020-00, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) - Process 305210/2018-1, and by FAPESP Process 2016/24561-0. These supports are gratefully acknowledged.

Data Availability. Data sets generated during the current study are available from the corresponding author upon reasonable request.

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3.4 Complementary Discussions and Studies under development

3.4.1 Sun-grazing versus thermal disruption

In this study, we investigated various aspects of the km-sized known NEO population. At first, we followed an approach similar to the one adopted by Gladman et al. (2000). In the paper, they state that an asteroid was removed from the integration if it collided with some massive body or if it was ejected from the Solar System. They found that more than half of the sample was eliminated by the Sun-grazing process, which means that the object's pericentre was smaller than the solar radius, so they considered that the bodies collided with the Sun (Gladman et al., 2000).

This fate is common for the NEOs that reach semi-major axes $a > 2$ au because they tend to suffer the effects from the 3:1 mean-motion resonance with Jupiter and the ν_6 secular resonance between 2.0 and 2.5 au, which increases their eccentricities to 1. However, the authors state that it may also occur for bodies with a semi-major axis between 1.3 and 1.9 au, where the ν_2 and ν_5 secular resonances make the bodies' eccentricities oscillate, decreasing their pericentres to the radius of the Sun.

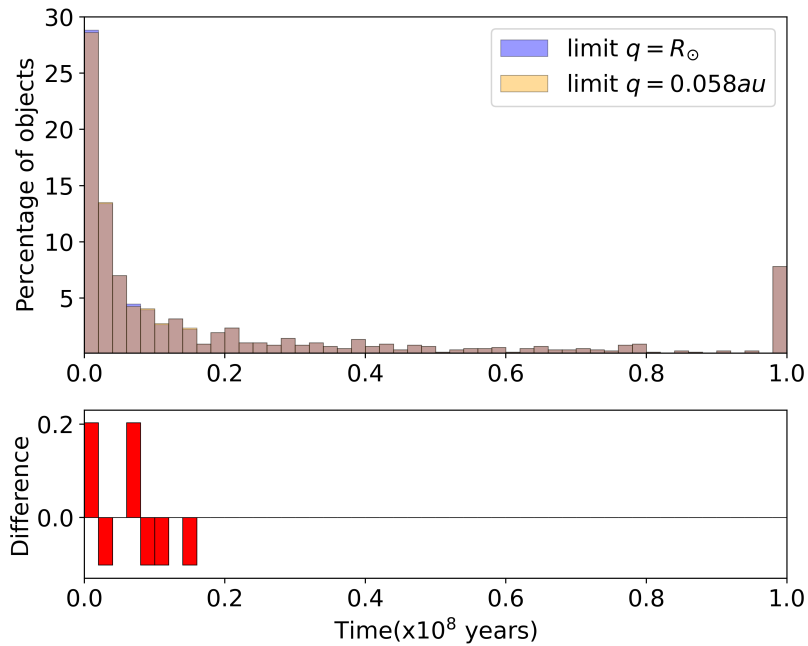


Figure 5 – Distribution of lifetimes for all objects studied. In the top plot, the orange colour represents the distribution of the total lifetimes considering the thermal disruption limit at 0.058 au, while the blue bars show the distribution considering the limit for Sun-grazing at the physical radius of the Sun, shown as percentages of the total number of objects in the studied population. The brownish colour shows the overlap of the two distributions. In the bottom plot, it is shown the difference (also in percentage of the total sample) between the scenario with the limit for a Sun-grazing fate with the pericenter of the object at the radius of the Sun ($q = R_{\odot}$), and the scenario with the thermal disruption ($q = 0.058$ au).

But as most of the bodies are predominantly affected by close encounters being pushed to the main belt, the 10 Myrs dynamical lifetime of the NEO population is not ruled by the resonances previously mentioned in a first approximation (Gladman et al., 2000). However, more recent studies showed that thermal disruption acts on the km-size objects at around 0.058 au (Granvik et al., 2016). Therefore, before the objects hit the Sun, they are probably destroyed by thermal forces.

Figure 5 (top) shows the distribution of lifetimes of all objects in the studied population in both scenarios, with and without thermal disruption taken into account. In the top plot, notice that the bars are mostly overlapping, which shows that the lifetime distribution is almost the same in both scenarios. The bottom plot of Figure 5 shows the difference (in the percentage of the total population studied) between the case without thermal disruption and the case with thermal disruption. Notice that there are small differences up to ~ 15 Myrs, which means that objects mostly affected by the different scenarios are those with lifetimes shorter than 16 Myrs. However, the total difference is still less than 1%, which means that only a small part of the studied objects have a significant impact on their life span. It shows that the objects that would be eliminated due to a collision with the Sun, are removed just a short time before due to the thermal disruption.

It has a direct impact on the statistics of the fates of this population. Without thermal disruption, almost half of the objects are eliminated by ejection. Meanwhile, only 16.9% of objects are ejected when the thermal effects are taken into account and those that would be ejected end up being eliminated by thermal disruption. Apart from the fates, there is no significant difference for the rest of the analysis of the routes and lifetimes, for instance (see Table 1 in Liberato et al. (2023) in Section 3.2 of this thesis). Therefore, since it shows that there is no notable divergence, regardless of the assumption, we chose to use the most accurate one by taking into account the thermal disruption for km-size objects.

3.4.2 Collisions with terrestrial planets

It is shown that 7.5% of all the studied objects collided with the planets (Table 1 in Liberato et al. (2023) presented in Section 3.2) and that they tend to present smaller variations in orbital inclinations during their evolution when compared with objects with different fates (Liberato et al., 2023). Therefore, considering all the 985 large known NEOs studied, Table 1 presents our results on the statistics of impacts with planets.

As it was expected, it is possible to notice from the results in the second column of Table 1 that Venus and Earth are the planets with the highest rates of collision, suffering respectively 54.05% and 33.78% of the total number of impacts. Due to the combination of gravitational perturbation and shorter orbital periods, Venus and Earth are the planets with the most influence on the objects in the terrestrial planets region (Gladman et al., 2000; Bottke et al., 1994).

Furthermore, the third column shows the mean impact frequency for km-size objects. We find that for the Earth it is 2.5×10^{-7} objects per year, which means that the Earth

Planet	Percentage of collisions	Average impact frequency(objects per year)
Mercury	4.05	3×10^{-8}
Venus	54.05	4×10^{-7}
Earth	33.78	2.5×10^{-7}
Mars	2.71	2×10^{-8}
Jupiter	5.41	4×10^{-8}

Table 1 – Known large NEO impact statistics, considering the sample of 985 objects. The second column presents the percentage of impact with each planet concerning the total number of collisions, while the third column presents the average frequency of impact per year.

would suffer, on average, one very destructive impact event every 4 million years. However, this impact rate is underestimated since there is strong evidence that the NEO population is in a steady state and therefore is constantly resupplied from outer groups of objects (Hughes, 2000; Bottke et al., 2000; Greenstreet et al., 2012a; Granvik et al., 2018).

Table 5 of Liberato et al. (2023) presents the statistics of fates in a steady-state scenario for the case with and without thermal disruption. In this scenario, we considered that for each object eliminated, another object with the same lifetime and fate replaced it until the sum of the lifetimes reached the 100 Myrs simulation time span. So, for instance, we assume that an object that collided with the Earth after 10 Myrs became 10 objects that collided with the Earth during 100 Myrs in the steady state scenario.

Doing a parallel with that analysis, the population of large known NEOs became a sample of 41841 objects in the scenario without thermal disruption ($q < R_{\odot}$), where 3.6% of them collided with the planets. Taking into account that 33.78% of the collisions happened with the Earth, we find about 420 impacts over 100 Myrs. Using the same approach for the case with thermal disruption ($q < 0.058$ au), we obtained that from the 1.5% of collisions in the 82636 objects, approximately 508 of them impacted the Earth in 100 Myrs. These values give an estimated average Earth impact frequency of approximately 1 km-size NEO every 0.2-0.24 Myrs.

Estimates from previous works (Grieve and Shoemaker, 1994; Stuart and Binzel, 2004; Michel et al., 2005; Shoemaker and Wolfe, 1987) show that the frequency of impacts for a km-size object to collide with the Earth is once every 0.1-1 million years, which is in great agreement with our results. In the steady-state, the impact flux ratio of Venus/Earth and Mercury/Earth is estimated to be 1.12-1.6 and 0.75-1.2, respectively (Vokrouhlický et al., 2000; Scheeres et al., 2004; Greenstreet et al., 2012b; Granvik et al., 2018). Our results provide, in the steady-state scenario, an impact flux ratio of 1.4-2 for Venus/Earth and 0.13-0.27 for Mercury/Earth. For Venus, our results are in good agreement with the expected impact frequency. However, for Mercury, we found a smaller impact ratio than the previous estimates. The difference is probably due to the poor statistical sample, but our result still presents some reasonable agreement in this case. For the other planets, our statistics aren't very reliable due to the small number of impacts. Furthermore, Mars and Jupiter suffer more from impacts from other sources of objects, such as the Mars Crossers, Main belt asteroids and Jupiter family comets. So the impact rate from NEOs alone would

not be a sufficient approximation of the impact rate on these planets. (Scheeres et al., 2004; Shoemaker and Wolfe, 1987; Leake et al., 1987; Vokrouhlický et al., 2000)

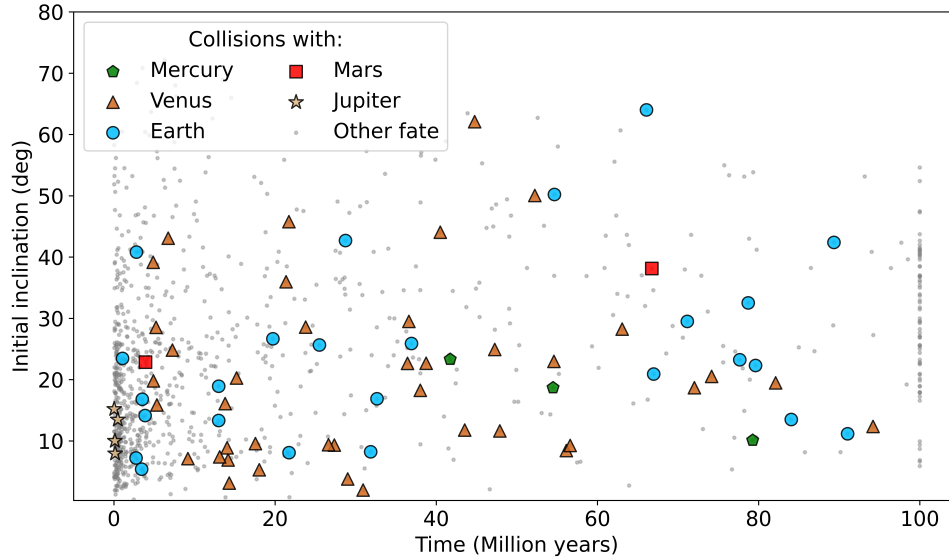


Figure 6 – Distribution of the lifetime of the studied NEOs versus their initial orbital inclinations. The grey dots show the distribution of all objects with different fates, while the coloured markers show the distribution of the bodies that collided with the planets.

In Figure 6 it is shown the distribution of initial inclinations for the studied NEOs that collided with the planets and their respective lifetimes. As discussed previously, the dispersion of inclination for objects that collided with planets is small, where the median value of the distribution moves from 19.2° in the initial inclinations, to 23.5° at the final inclination distribution (See Fig. 6 in Araujo et al. (2023) presented in Sec. 3.3 of this thesis).

It is interesting to notice the 4 objects that impact Jupiter in the first one million years of simulation. They are classified as NEOs but lie inside the Jupiter-family comets region (JFC), which is why they were classified as *initially JFC* in Liberato et al. (2023) (Sec. 3.2). These objects are strongly perturbed by Jupiter and, due to their relatively low inclinations, the collision happens in a short timescale. For Mercury and Mars, notice that they suffer more impacts from objects with intermediate inclinations and in longer timescales, however, one must be careful in concluding since there is not a significant number of cases to obtain reliable statistics.

Furthermore, there are no impacts of objects with inclinations up to 10° after approximately 30 Myrs, which means that objects with nearly co-planar orbits have shorter lifetimes, as expected, due to their higher probability of close encounters and collisions (Araujo et al., 2018b). However, as discussed before, the impacts of objects with low inclinations should also be constant in a steady-state scenario since the NEO population is constantly resupplied by nearly co-planar objects from the main belt (IAU-MPC, 2023; Morbidelli et al., 2015; Zain et al., 2020).

For Venus and Earth, it is noticeable that there is a nearly constant flux of objects colliding with these planets, while for the others it does not seem to happen. It shows that

the flux of objects with intermediate inclinations that impact Venus and Earth is nearly constant. Additionally, it is possible to infer that if we had continued the simulations for the objects that survived the 100 Myrs, we would probably find that more than 80% of them maintained the constant flux of impacts on Venus and Earth.

Finally, this shows that the orbital inclination plays an important role in the evolution of NEOs. Although objects with low inclinations have a higher probability of collision in short timescales, our results show that the population of large NEOs with intermediate inclinations are also a source of impacts and can present a risk for Earth and Venus.

3.4.3 Vatiras and Matiras

NEOs are usually divided into four sub-classes: Amor ($1.017 < q < 1.3\text{au}$), Apollo ($a > 1.0\text{ au}$ and $q < 1.017\text{ au}$), Atens ($a < 1.0\text{ au}$ and $Q > 0.983\text{ au}$), and Atira ($0.718 < Q < 0.983\text{ au}$), where q is the perihelion and Q is the aphelion of the object's orbit. This is a population of objects that are frequently changing sub-classes due to the planetary close encounters and resonance effects.

Other sub-populations with orbits internal to Venus and Mercury have been studied, the Vatiras and Vulcanoids. Vatira is the population of objects with orbits entirely internal to Venus and exterior to Mercury, while the objects with orbits entirely internal to Mercury are usually called Vulcanoids. The latter is theorised to be a ring of leftover material from the formation of the Solar System that would be the cause for the topography observed on Mercury's surface (Perrine, 1902; Weidenschilling, 1978; Wetherill, 1988; Cameron et al., 1988).

The first Vatira asteroid, 2020 AV2, was discovered in 2020 (Bolin et al., 2020; Greenstreet, 2020; De La Fuente Marcos and De La Fuente Marcos, 2020). Despite the extensive surveys for objects internal to Venus (Durda et al., 2000; Steffl et al., 2013; Ye et al., 2020; Sheppard et al., 2022), no other Vatiras were discovered and none of the searches found any confirmed vulcanoids. It is estimated that there are about 1,000 km-sized NEOs at any time in the steady-state population, of which about 0.22% are Vatiras (Greenstreet, 2020; Granvik et al., 2018). Meanwhile, it is estimated that the vulcanoid zone may contain a considerably large number of km-sized objects (Durda et al., 2000; Evans and Tabachnik, 1999; Vokrouhlický et al., 2000).

The decline in the putative vulcanoid population is most likely attributed to the Yarkovsky effect, which causes asteroids to gradually drift into the Sun to less stable zones with more perturbation from the planets (Vokrouhlický et al., 2000), and to the collisional evolution of this population (Stern and Durda, 2000). Their dynamic properties influence the lifespan of Vatiras and Vulcanoids. Most km-scale vulcanoids are estimated to escape the inner-Mercury zone in less than 1 Gyr but between 20 and 100% of initially 10 km-sized objects may persist beyond the age of the solar system, depending on their material and dynamical properties (Evans and Tabachnik, 1999; Stern and Durda, 2000; Durda et al., 2000).

The dynamical characteristics, longevity, collision rate, size, and detection of Vatiras

and Vulcanoids are still being studied, and additional research is needed to fully understand these populations. Therefore, using the same simulations as in the previous studies shown in this Section, we look for objects in the studied known large NEO population that were transported to inner regions and their characteristics to obtain new pieces of information to increase the knowledge of such classes of objects.

The term "vulcanoids" is mainly used in the community to describe objects that have been inside Mercury's orbit since the early stages of the terrestrial planet's formation, which is not the case for the objects studied in this work. Therefore, since "Vatiras" is a portmanteau word for *Venus* and *Atiras*, we decided to use *Matiras* to describe the objects that would have been recently transported from outer regions into the inner Mercury's orbit zone.

Usually, the Vatiras are only limited in apocenter so that they are not allowed to wander beyond Venus, but the perihelion is normally not limited. However, with the usual assumption, Vatiras can cross Mercury's orbit and suffer close encounters, leading them out of the region in a shorter time. Therefore, considering all of the 985 known large NEOs in this analysis, the Vatira zone was chosen to be bounded by Mercury's aphelion at 0.466 au and Venus' perihelion at 0.718 au, while the Matira zone is bounded by Mercury's perihelion at 0.307 au and the thermal disruption limit at 0.058 au, so that objects inside these limits do not cross the planet's orbits. We assume that a NEO becomes a Vatira or a Matira when it enters one of these zones and stays for at least 2000 orbital periods in it. If the object stays more than 50 orbital periods out of the limits we consider that it left the zone and thus lost the Vatira/Matira classification. This assumption deals with the fleeting changes due to short-period resonant effects.

Figure 7 shows the Matira and Vatira zones in the (a, e) space in grey and orange, respectively, as well as the perihelion and aphelion for all the terrestrial planets and Jupiter. The circles represent the initial conditions of the known large NEOs studied that were transferred to the internal zones.

The objects that became Vatiras presented an initial semi-major axis between 0.5 and 2.5 au and orbital inclinations up to 50° . As expected, the objects that become Vatiras are usually those with perihelions and/or aphelions close to Earth or Venus' orbits. As shown in Liberato et al. (2023) and Araujo et al. (2023) (and references therein), the close encounters are the main effect acting to modify the NEOs' orbits.

The results show that 25 NEOs became Vatiras during the 100 Myrs of simulation, which represent 2.54% of the studied population. Using the same steady-state approach as described in Section 6 of Liberato et al. (2023), we found that 1.99% of the large NEOs become Vatiras. However, these objects spend only $\sim 23\%$ of their lifetimes inside the Vatira zone, on average. So, we find that the number of Vatiras at any time in a steady-state scenario is 0.46%, which is close to the expected steady-state Vatira population estimated by (Greenstreet et al., 2012b).

These objects take, on average, 12.7 Myrs to become Vatira for the first time and have a median lifetime of 8.86 Myrs. Additionally, 60% of the Vatiras end up colliding with the planets and 16% survive, indicating that these objects are most likely those referred to as "Always NEOs" in Liberato et al. (2023).

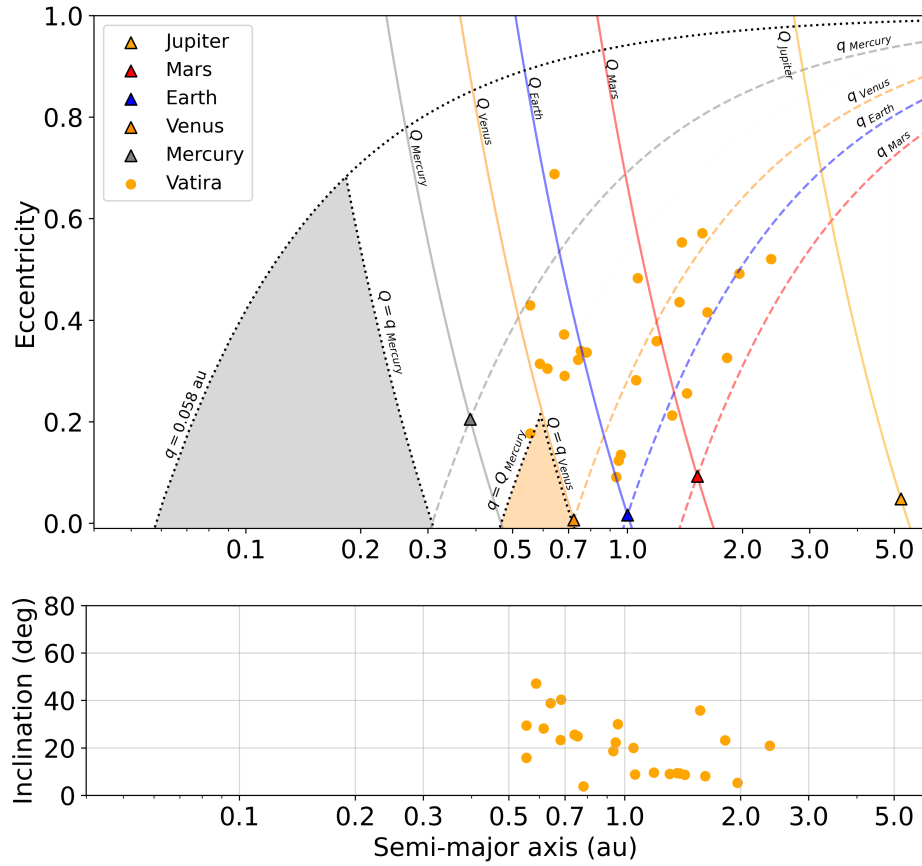


Figure 7 – Initial conditions of the studied NEOs that became Vatiras in the simulations. The top plot shows the initial (a, e) distribution of these objects in the grey and orange dots, the pericenters (dashed lines) and apocenters (solid lines) concerning the terrestrial planets and Jupiter, and the chosen boundaries for the Vatira and Matira zones in orange and grey, respectively. The bottom plot shows the initial distribution of (a, i) for the objects that became Vatiras.

None of the studied NEOs became a Matira according to our considerations. We found that 10 of them eventually present an orbit entirely internal to Mercury but for a very short period (~ 4000 years) just before hitting the Sun and with the perihelion smaller than the thermal disruption limit. Our results agree with previous studies made by [Greenstreet \(2020\)](#), which also did not find objects transported to the inner Mercury zone. Therefore, it is possible to say that it is very unlikely for large NEOs to reach orbits internal to Mercury in safe and stable configurations. If this population really exists, it may be very small and probably not hazardous for our planet.

Our results show that there must exist a small, but non-negligible, population of km-size objects internal to Venus that stay for a few hundred thousand years as Vatiras, as predicted in other works. These objects are also a significant source of collisions with Venus and Earth, so this population should be closely monitored due to their significant impact risk. Furthermore, it is unlikely for large NEOs to reach orbits internal to Mercury and remain as Matiras. So, if there is a population of km-size objects inside Mercury's orbit, they are most likely the primordial class of Vulcanoid objects.

Finally, we must point out that only the gravitational perturbations were taken into account in this study. However, secondary effects such as general relativity and Yarkovsky could affect the results, though their influence may be nearly negligible due to the short timescales in which the orbits of the minor bodies change during the simulations. Nevertheless, in order to obtain more accurate results, we intend to run new simulations taking into account the mentioned secondary effects to estimate their contribution and use short timesteps to accurately resolve the orbits of the objects close to the Sun.

3.5 Conclusions and Comments

We present a detailed analysis of the evolution of a population of known large near-Earth objects. We find that the most common path taken by near-Earth objects in the Solar System is to move toward the JFC region, then be thrown toward the Sun by strong perturbation from Jupiter, and finally be destroyed by thermal effects. Nearly 60% of studied objects were first moved to the JFC area, and 77% of the objects ended up inside it before moving on to achieve their destiny. 14% of objects never leave the NEO region and are the main source of collisions with planets and survivors.

At the same time, the MAB region appears to be a transition zone for near-Earth objects because nearly 35% of objects are transported there, but only 0.5% end their life inside the MAB region. We also show that nearly 10% of the large near-Earth objects studied reached the CEN region, and although most of the objects were briefly removed from the region, some of them remained.

The average orbital inclination of the studied objects tends to increase by a factor of 1. Fluctuations in inclination tend to be small, and the large differences at the end of the NEOs' lives are due to gradual accumulation processes. We show that the inclination is an important factor influencing the lifetime of objects in the NEO region. Over time, the object tends to evolve towards intermediate inclination values, which seems to be the most stable configuration for long-lived large NEOs. The only bodies that have survived more than 60 million years are those that originally had, or evolved into, a "safe range" of inclination.

Additionally, we were able to determine the frequency of km-size object collisions with Mercury, Venus, and Earth, where over 80% of the NEO collisions occur. Objects with low inclinations pose a danger due to their collision in a short timescale, but objects with moderate inclinations are also always at high risk of collision. High-energy collision with Earth is estimated to occur every 200,000 years and every 120,000 years with Venus, in a steady-state scenario. Furthermore, Vatiras present a 50% chance of colliding with Venus or Earth, and more than 14% chance of survival. This suggests that this population exists and could pose a significant threat to Earth. On the other hand, it is highly unlikely that a km-sized object consisting of ex-NEO exists in Mercury's inner zone.

3.5.1 Future Works

Through the careful study of the population of large known NEOs, we obtained interesting results that show the influence of their orbital parameters on their evolution through the Solar System. However, NEO dynamics is a rich field full of unknown information and studies to be made.

It is known that objects from distant reservoirs, such as Centaurs and TNOs, have a small but existent contribution to the NEO population (Levison and Duncan, 1997; Morbidelli et al., 2002; Horner et al., 2004; Wood and Horner, 2015; Araujo et al., 2018a). One of the most interesting results in Liberato et al. (2023) is that approximately 10% of the known large NEO population in a steady state can reach orbits as far as the centaurs region and remain in it for 2 Myrs, on average. The lifetime of Centaurs is estimated to be in the order of 10 Million years (Levison and Duncan, 1997; Di Sisto and Rossignoli, 2020),

so it is possible that these NEOs became Centaurs during their stay beyond Jupiter. So, in the most recent ongoing work, we'll study the distribution of NEOs in the centaur region, their lifetimes, their escape zones and their evolution through a series of new simulations with clones of these objects. We intend to investigate how the population of the known large NEOs transported to the centaur region compares to the known centaur population in size, orbital characteristics and lifetimes.

Another interesting aspect we have not explored yet is the capture of NEOs as co-orbital objects to the planets. In a three-body problem, the objects are in a co-orbital configuration when the separations between the three objects are kept closely constant in the non-inertial reference frame. Thus, two of these objects are in a 1:1 MMR around the central body. It was already shown that terrestrial planets can also capture asteroids in 1:1 MMR, both as trojans around L4 and L5 lagrangian points and as quasi-satellites around L1 and L2 lagrangian points (Schwarz and Dvorak, 2012; Galiazzo and Schwarz, 2014). Because NEOs constantly cross the orbits of the planets and suffer several close encounters during their lives, it is possible that some of them would be captured. Therefore, in a future step, we'll analyse the data from the simulations to check if any of the studied NEOs eventually were captured in a 1:1 MMR with some of the terrestrial planets and to look for close encounters that could have led to the capture of objects in co-orbital configurations.

The last and more ambitious point we intend to work on in the future is to create a 3D map of the NEO region. As discussed in Section 3.4.3, there are a significant number of large NEOs that eventually become Vatiras, while none of them become Matiras. Additionally, in Liberato et al. (2023) is also shown that it seems like there is not a preferential configuration for the objects to be transferred to another specific minor body region. Therefore, taking advantage of the recent advances in Machine Learning methods, we intend to create a stability map of the NEO region using tree-based models applied to simulations of the 3-body problem (Tiago F.L.L. Pinheiro, private communication, September 2023) to identify the preferential configurations for transferences to each different region and class. Then, using the neural network algorithms applied to the identification of asteroids under the effects of MMRs and secular resonances (Carruba et al., 2021a,b, 2022, 2023), we intend to investigate the resonant angle of the objects that were transferred. The goal will be to identify which are the dynamical perturbations acting on each one of the objects to classify and determine the most likely conditions for each transference.

4 Detection of astrometric binary asteroids

4.1 Contextualization

The Gaia mission was designed to succeed the Hipparcos mission and provide unprecedentedly high astrometric accuracy, even for very faint objects in space (Hestroffer et al., 1999; Mignard, 2002; Tanga et al., 2007). During the careful mapping of our galaxy, the Gaia telescope also observed several thousands of Solar System objects. In Gaia Data Release 2 (DR2) there are only approximately 14,000 asteroids with preliminary astrometric and photometric data (Gaia Collaboration et al., 2018). Meanwhile, Gaia Data Release 3 (DR3) provided ultra-high accuracy astrometric and photometric data for more than 150,000 asteroids (Tanga et al., 2022).

It was foreseen that the accuracy achieved by the Gaia mission would allow the detection of binary asteroids using the astrometric data (Mignard et al., 2007; Tanga et al., 2007; Pravec and Scheirich, 2012). In 2022, Gault et al. observed two stellar occultations by the asteroid (4337) Arecibo and detected the presence of a satellite. The occultation events provided accurate astrometric measurements and estimates for the diameters and separation of the components (Gault et al., 2022). Therefore, in Tanga et al. (2022) it was analysed the data from 38 transits in Gaia DR3 for Arecibo, which was still unpublished at the time, and it was possible to retrieve the astrometric signal from the secondary body.

So, with Arecibo as the proof of concept showing that the detection of satellites using Gaia DR3 astrometric data is possible, we decided to search for binary asteroids using astrometric measurements from the Gaia mission.

In Section 4.2 I present the manuscript entitled "Candidate discoveries of binary asteroids by systematic search in Gaia DR3 astrometry", which is in the final stages of preparation before submission. In that work, a careful and systematic blind search for binary asteroids in Gaia DR3 astrometric data is performed. Periodic signals representing binary systems were meticulously detected and selected in the residuals obtained from orbital fitting based on astrometric data. Next, a series of validation tests and filtering based on the physical properties of the binary system candidates is made. Finally, a list of 67 selected best binary asteroid candidates is obtained, which provides a solid starting point for further investigations, including confirmation and detailed characterisation of these systems.

Finally, in Section 4.3 I present some comments about this work and on the future steps we will be working on.

4.2 Candidate discoveries of binary asteroids by systematic search in Gaia DR3 astrometry

Astronomy & Astrophysics manuscript no. output
November 8, 2023

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Candidate discoveries of binary asteroids in *Gaia* DR3 astrometry

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Received / Accepted

ABSTRACT

Context. Asteroids with companions constitute a sample of excellence for studying the collisional and dynamical evolution of minor planets. The currently known binary population has been discovered by different complementary techniques, that produce for the moment a strongly biased distribution, especially in a range of intermediate asteroid sizes (≈ 20 to 100 km) where both mutual photometric events and high-resolution adaptive optic imaging are poorly efficient.

Aims. A totally independent technique of binary asteroid discovery, based on astrometry, can help to reveal new binary systems and populate a range of sizes and separations that remain nearly unexplored.

Methods. In this work, we describe a dedicated period detection method and its results for the *Gaia* DR3 data set. This method looks for the presence of a periodic signature in the orbit post-fit residuals.

Results. After conservative filtering and validation based on both statistical and physical criteria, we are able to present a first sample of astrometric binary candidates, to be confirmed by other observation techniques **such as photometric light curve and stellar occultations.**

1. Introduction

Binary asteroids have attracted the attention of the scientific community due to their interesting properties and the significant impact they have on our understanding of the solar system. Unlike single asteroids, binary systems offer unique insights into many fundamental processes, including the formation and evolution of planetary bodies, collision dynamics, and gravitational interactions.

Numerical simulations suggest the existence of nearly equal-sized binaries as a byproduct of catastrophic collisions (Durda et al. 2004) but they remain essentially unknown. On the other hand, multiple craters on Mars demonstrate that asteroid binaries with properties not represented by the known sample should exist, or have existed (Vavilov et al. 2022). More in general, the formation of asteroid companions by fragment ejection and in-orbit re-accumulation (Walsh & Richardson 2006, Walsh et al. 2008, Čuk 2007, Pravec et al. 2010, Jacobson et al. 2013, Madeira et al. 2023) seems to be common among Near Earth Asteroids (and probably small Main Belt objects) but the collisional evolution is also expected to play a role (Doressoundiram et al. 1997, Michel et al. 2001, Durda et al. 2007, Jutzi 2019), with an undefined boundary between the two creation mechanisms. However, some open questions on the origin of binaries and the evolution of asteroids cannot be answered without a larger number of known objects and a better knowledge of the sample.

The presence of asteroid companions has been revealed by different techniques, such as high-resolution imaging from ground-based and space-based telescopes, photometry, radar

ranging and stellar occultations. When taken together, these different approaches are complementary and cover a wide range of separations and size ratios for the system components. However, the known population of binary asteroids is still strongly biased.

While imaging favours large separations of the primary and the secondary, and bright primaries in the case of Adaptive Optics, photometric studies, based on detecting mutual events, strongly favour compact systems (Merline et al. 2002, Pravec et al. 2006, Richardson & Walsh 2006). Radar techniques are strongly limited in range and are efficient for Near Earth Asteroids (Ostro et al. 2002).

Some satellites have also been discovered by space probes and studied during close encounters. While they constitute a precious sample of detailed information, in statistical terms, their contribution to the knowledge of the global population of binaries is limited. Astrometric detection of binaries cannot solve alone all these problems, but can very usefully fill an unexplored space of exploration (Pravec & Scheirich 2012). The astrometric signature of the presence of asteroid satellites is expected to show up in the residuals of the asteroid motion (on the sky or, equivalently, concerning the heliocentric orbit) due to the difference between the position of the photocenter (the one usually provided by the observations) and the centre of mass of the system. This difference, which in principle can also be due to the irregular shape of a single object, is enhanced by the presence of a satellite.

Anomalous residuals in the astrometry, linked to the presence of a satellite, have been revealed in the case of (90482)

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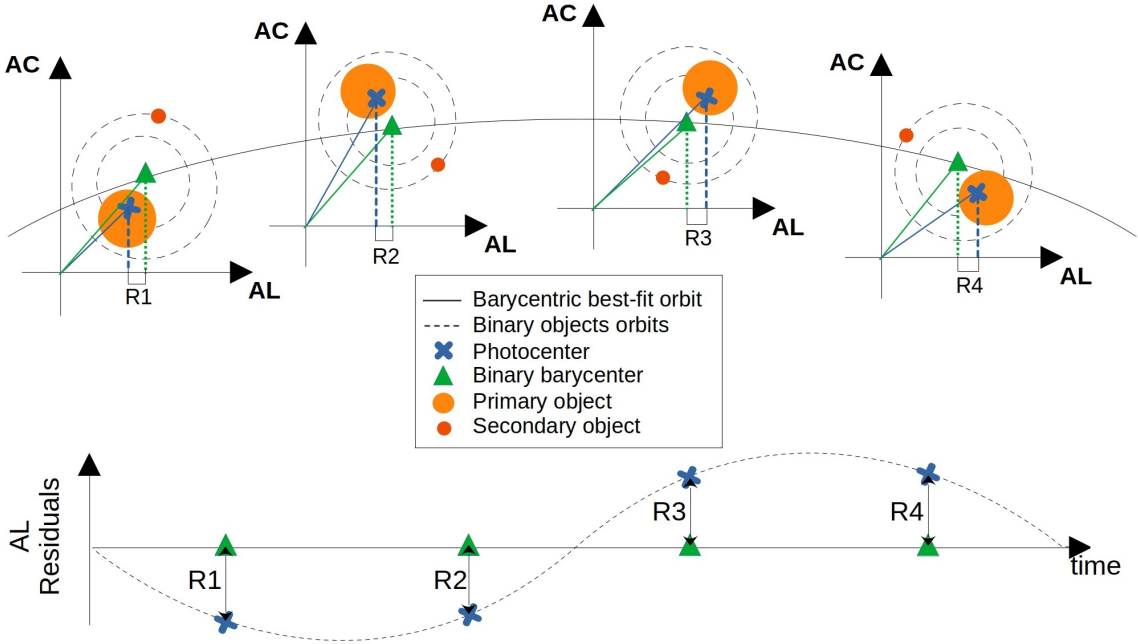


Fig. 1: Representation of a simplified case where, *Gaia* satellite would be observing a binary system perpendicularly to the plane of rotation of the bodies, along with the projections of the positions of the barycenter and the photocenter on the AL direction and the representation of the orbital fit residuals' projection in the along-scan direction. AL direction is represented horizontally for simplicity, but it can take any orientation in reality, slowly rotating by some degrees on a scale of several hours.

Orcus (Ortiz et al. 2011). For TNOs, the effect is amplified by the large separation of the components, particularly in cases of high size ratio (secondary/primary).

The astrometric signature is much harder to detect for Main Belt asteroids, in general, since it requires much more precise astrometry to reveal a perturbed motion due to a companion that is not spatially resolved, in general. A rather solid detection, the first using *Gaia* astrometry, was obtained for (4337) Arecibo (Tanga et al. 2022). Also in this case, however, the presence of a satellite was already known. A systematic search of astrometry for new binary systems is a much more complex task. Only the exploration of a large data set of homogeneous measurements of extremely high quality can potentially be successful. The data produced by the *Gaia* mission of ESA represent the main source available today for this search. A first attempt on the very limited data set (in time range and number of objects) provided by *Gaia* DR2 remained unsuccessful (Segev et al. 2023).

In the following, we present a blind search of astrometric binaries in the *Gaia* DR3 asteroid astrometry. Our exploration represents a first step only, in which we focus on the detection of periodic signals (wobble, in the following) in the residuals obtained from orbit adjustment to the data. This approach limits, for the moment, our investigation to sets of astrometric positions collected in short time spans. As a consequence, short-period systems are favoured. The result of our search is also filtered on the base of rather strict criteria. These choices produce results that are certainly not comprehensive of what can be obtained from *Gaia* data. Nonetheless, it provides a first consolidated set of candidate detections that can be fruitfully explored by other techniques for confirmation.

The article is organised as follows. In Section 2, we recall the main properties of the data set that we explore and the goal of the search. Section 3 presents the method of period search. The selection, filtering and validation of the candidates found, both by

statistical and physical criteria, is presented in Section 4. Section 5 presents the content of the final list of binary candidates. We put our findings in a broader context in Section 6 and resume the work, with future perspectives, in Section 7.

2. Astrometry and binary signatures: data set and model

The asteroid astrometry in *Gaia* DR3 for a large number of asteroids provides an outstanding opportunity for a search of astrometric signatures produced by possible satellites. The properties of *Gaia* astrometry have been illustrated in detail by Tanga et al. (2022). Here we will just recall a few properties specifically relevant to our search.

The first one is the time distribution of observations. The two *Gaia* telescopes scan the sky continuously with a 6-hour rotation period. The two Fields of View (FOV) sweep the same area of the sky 106 minutes apart. The spin axis precesses in such a way that a large field overlap is granted every subsequent rotation. The combination of this rotation/precession with the revolution around the Sun results in a sparse series of detections (also called *transits* in the FOV) for any given source, fixed or moving. However, when the motion on the scanning path in the sky combines favourably with the position and displacement of a target source, a short consecutive series of detections over a few satellite rotations is possible.

Over the coverage of *Gaia* DR3 (34 months), it is rather common to obtain sequences of a few consecutive observations spanning a couple of rotations (12h - 4 detections) for each object. A few occurrences of longer sequences with several rotations up to 10-12 detections (5-6 revolutions) can also happen, although less frequently.

As will be discussed in the following section, the length of time windows of consecutive data and the presence of constant

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periods in the data sampling control, respectively, the longest detectable period in our analysis, and the possible emergence of spurious frequencies. At the same time, irregular sampling allows the exploration of a large range of frequencies (Eyer & Bartholdi 1999, VanderPlas 2018).

Also, the nearly mono-dimensional astrometry provided for each transit brings accurate information only in the direction of the scan (along-scan, AL). The only measurable residual from orbital fitting is the projection of the total residual onto the AL direction, whose direction is known from the attitude data of the satellite. The direction of the total post-orbital fit residual in the sky, however, is not directly measurable from *Gaia* astrometry alone at a given epoch (or in an interval of time in which the geometry of the system concerning the scan direction does not evolve). Constraints on the total wobble in the astrometry, and the possible primary-secondary separation, are the result of applying some physical constraints to the measured wobble projection and period.

For this first search for astrometric binaries, we use the simplest first-order model for the wobbling motion, assuming systems composed of uniformly illuminated spheres, of equal bulk densities and albedos. The other important assumption is that the components are not resolved so that the wobble is generated by the difference in position between the barycenter of the system (to which the orbit is adjusted) and the photo-center. Given the size of the *Gaia* pixel (60 mas) in the AL direction, this should be the case for a wide range of binaries in a reasonable range of sizes.

Figure 1 illustrates the principles discussed, where at the top of the figure it is shown a representation of an ideal case where *Gaia* is observing a binary asteroid perpendicularly to the plane of rotation of the objects around the barycenter, the along-scan direction (AL) of the *Gaia* satellite is on the x-axis and the across-scan direction is on the y-axis. In principle, at any given epoch, the projection of the instantaneous wobble amplitude α for the satellite position on its orbit, projected along AL, is provided by the residual of *Gaia* astrometry to the orbital fit. The blue and green dashed lines represent the projection of the positions of the photocenter and the barycenter of the binary, respectively. The difference between these projections represents the AL residuals, as shown at the bottom of Fig. 1.

With the assumptions of uniform illumination and unresolved components, it is possible to derive the wobble amplitude as the difference between the position of the barycenter and the position of the photocenter. This is a function of the mass ratio q only (Hestroffer et al. 2010), scaled for the separation a :

$$\alpha = a \left| \frac{1}{1+q^{-1}} - \frac{1}{1+q^{-\frac{2}{3}}} \right|, \quad q \in]0, 1] \quad (1)$$

This function (Fig. 2) has a maximum at $q_{\max} \approx 0.154$ (corresponding to a size ratio $k = \sqrt[3]{q_{\max}} = 0.536$) and tends to zero at the extremes of the range of $q \in]0, 1]$, i.e. for a vanishingly small satellite or equal-sized components.

During a single transit in the Astrometric Field of *Gaia* (about 40 seconds), up to nine consecutive positions are obtained. We fit all *Gaia* DR3 astrometry for each asteroid by a version of the ORBFIT software¹, optimised to exploit the full accuracy of *Gaia*, following the same procedure as in Gaia Collaboration et al. (2018). From the orbital fit, for each astrometric point, a residual is obtained in the AL direction.

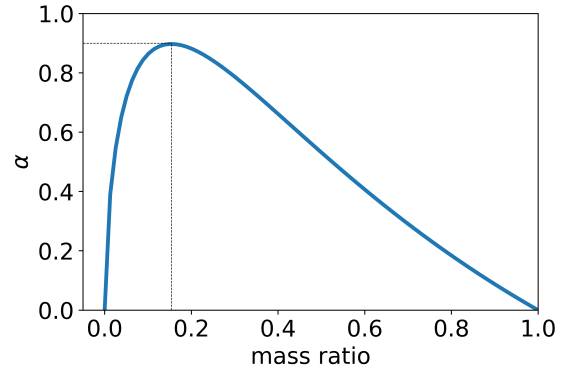


Fig. 2: Plot of the amplitude of the photocenter wobbling as a function of the binary mass ratio, as described in Eq. (1). In this example, we use a separation $a = 10$ mas, which means that we would observe a maximum photocenter wobbling of 0.9 mas for a mass ratio $q \approx 0.1538$.

Given that the observation geometry over that time span is nearly constant (and a relative displacement of a satellite negligible) we average the residuals from all transits from one observation into a single transit. Also, their standard deviation provides uncertainties on the measured residual itself. The average AL residuals per transit, and their uncertainty, are the data on which we base our analysis. To prevent future confusion throughout the work, we will refer to the residuals from the orbital fitting of the average transit observations in the along-scan direction simply as AL residuals from now on.

3. Wobbling Detection

For this first data exploration, our search targets intervals of time in which several consecutive astrometric measurements are available, sufficiently short to neglect any change of orientation of the asteroid with respect to *Gaia*. On the observations available over that interval, a period search is performed.

3.1. Sample selection

To easily identify the longest sequences of consecutive astrometric measurements, we perform a convolution of the observation epochs with a rectangular function and find the peaks of large data density, as shown in Fig. 3. In the left plot, we show the density of AL residuals over time for asteroid (3457) Arnenordheim, and the peak close to 450 days represents the 2.75-day window of time with 17 observations shown in the right plot. The rectangular function has a unity value over an interval of 10 days and zero elsewhere.

The considered threshold of 10 days is a compromise between the length of the time series and the resulting number of candidates, as longer time series allow for better frequency analysis but reduce the number of targets.

One should note that this selection method allows for gaps in the data sequence, where the observations are absent due to some technical reasons (missed observation, rejection for low quality). Over the whole DR3 data set of 156,801 asteroids, our selection extracts **30,030** objects with sequences satisfying the above-mentioned criteria.

Next, we identify the observations in each one of the windows and perform an outliers check, removing the points with

¹ See <http://adams.dm.unipi.it/orbfit>

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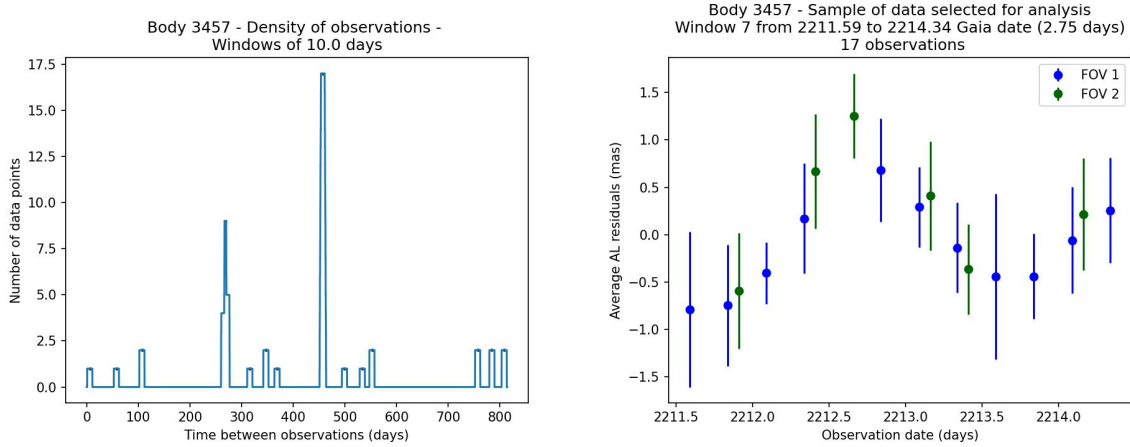


Fig. 3: Plots of the density of observations (number in 10 consecutive days) for asteroid (3457) Arnenordheim and selected sample of data. On the left plot, we show the resulting convolution of the observation time span in days versus the number of observations in each 10-day window. On the right plot, we show the sample of data at the peak of the 10-day window of search combining 17 observations. The x-axis is the observation date and the y-axis is the average AL residual from the orbital fit. Each dot represents one averaged set of transits observed in the field of view (FOV) 1 in blue and (FOV) 2 in green.

nominal values or standard deviations larger than 3σ of the dispersion of AL residuals in the window of search.

3.2. Period search

The Generalized Lomb-Scargle Periodogram (GLSP) (Zechmeister & Kürster 2009, VanderPlas & Ivezic 2015, VanderPlas 2018) is a statistical technique for analysing irregularly sampled time series data and identifying periodic signals in the data. The GLSP method is a generalisation of the classical Lomb-Scargle Periodogram (LSP) (Lomb 1976, Scargle 1982). As described in VanderPlas (2018), The GLSP corresponds to a weighted Least Square problem where a sinusoidal signal of unknown amplitude and phase plus an unknown constant are jointly estimated at each test frequency. Formally, using the notation from VanderPlas (2018), the GLSP $P(f)$ can be defined from the following equations:

$$y_{\text{model}}(t; f) \equiv y_0(f) + A_f \sin(2\pi f t + \phi_f) \quad , \quad (2)$$

$$\chi^2(f) \equiv \sum_{n=1}^N \left(\frac{y_n - y_{\text{model}}(t_n; f)}{\sigma_n} \right)^2 \quad , \quad (3)$$

$$P(f) \equiv \frac{\widehat{\chi}_0^2 - \widehat{\chi}^2(f)}{\widehat{\chi}_0^2} \quad . \quad (4)$$

Here, y_{model} Eq. (2) is the assumed true model: a sinusoid (unknown frequency f , amplitude A_f and phase ϕ_f , plus a constant offset term y_0 that may depend on the frequency). If the N data points of a time series y , $y(t_n) \equiv y_n$ for $n = 1, \dots, N$, correspond to the sum of the true model of Eq. (2) plus uncorrelated Gaussian noise of variance σ_n^2 for each of the n samples, then the weighted sum in Eq. (3) is a χ^2 random variable with N degrees of freedom. The GLSP computes the residual sum of squares of the weighted residuals (noted $\widehat{\chi}^2(f)$) obtained when adjusting a sinusoid with unknown amplitude and phase for each test frequency plus a constant, and compares it with the original

weighted sum of squares ($\widehat{\chi}_0^2$). Precisely, $\widehat{\chi}^2(f)$ (resp. $\widehat{\chi}_0^2$) is obtained by replacing y_{model} by the adjusted sinusoid (resp. by 0) in Eq.(3). The GLSP $P(f)$ in Eq. (4) is thus the relative reduction in the sum of square brought by the adjusted model at considered frequency f (with some abuse of notation on f). The higher $P(f)$, the smaller $\widehat{\chi}^2(f)$, which means that the model and the data are in greater agreement.

The GLSP is probably the most common technique to detect periodic signals in time series with irregular sampling. We opted for this approach because it has proven efficiency and it is computationally simple enough to allow for large-scale Monte Carlo simulations (this is an important aspect of our study, see next Section). The GLSP in Eq. (4) is implemented with the `ASTROPY` package (Astropy Collaboration et al. 2013, 2018, 2022), with error bars σ_n estimated as explained in the last paragraph of Sec. 2.

Given the sampling frequency and the time range of 10 days for our data sequences, we limit the search to periods between 3 hours and 3 times the length of the observations sample and apply our period search to all the asteroids in the **30,030** objects selected in the previous step.

The period search provides a periodogram for all the studied bodies, and they are very different depending on the time sampling of observations. The highest peak in the periodogram represents the period that best fits the sample. The left plot of Fig. 4 shows, as an example, the GLSP obtained for the asteroid (106016) 2000 SS293 from the sample of AL residuals shown in the right plot of the same figure. The red line is the GLSP from the fitting on the data of AL residuals in the current window of search. Using the frequency with the highest power from the GLSP on the data we obtain the sinusoidal fit with amplitude A and, along with the same time sampling and uncertainties, we run the GLSP to obtain the blue line that represents the profile of the periodogram only due to the sinusoidal signal. Finally, the spectral window (green line) is obtained by computing the Lomb-Scargle periodogram of a time series with constant unit amplitude².

² Precisely, the spectral window indicates, at each frequency, the reduction of the residual sum of squares (relative to the initial sum of

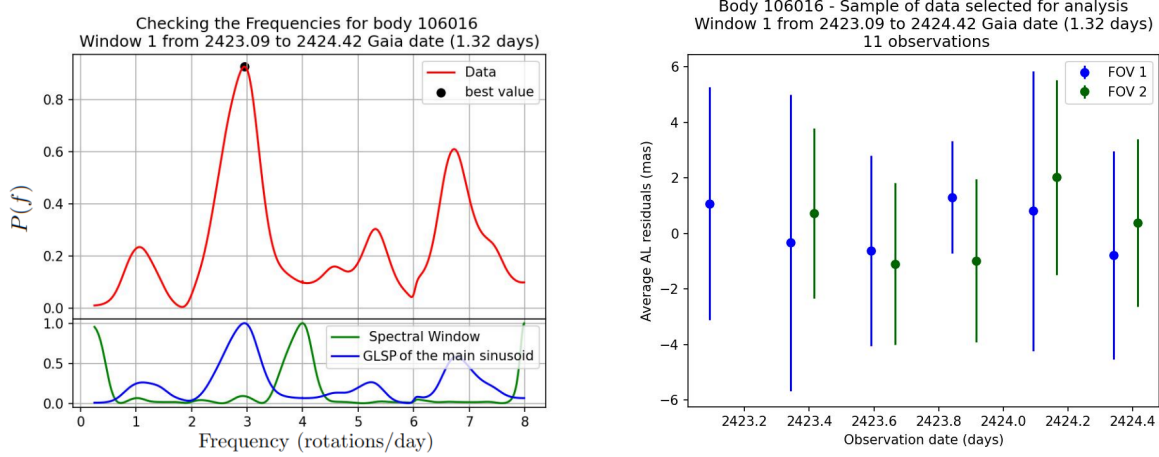
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Fig. 4: Examples of periodograms obtained for asteroid (106016) 2000 SS293 (left plot), with residuals shown on the right plot. The y-axis shows the GLSP $P(f)$ for each frequency shown in the x-axis. The red line represents the periodogram obtained for the data analysed. The blue line represents the GLSP obtained for a purely sinusoidal signal whose parameters correspond to the largest peak of $P(f)$ (about 3 cycles/day here), with the same time sampling as the data and the same error bars for the weights. Finally, the green line represents the spectral window of the time sampling. The right plot shows the AL residual time series that reproduces the periodogram on the left plot.

It is interesting to compare the shapes of the GLSP of the data (red curve in the left panel of Fig. 4), of the main estimated sinusoid (blue curve) and spectral window (green curve). The spectral window indicates the specific frequency pattern related to the specific time sampling in a time series. Similarities in the structures of the spectral window and the GLSP are often a clear sign that some peaks are fake (sampling-induced) rather than genuine signal periodicities. Similarly, the pure sinusoid analysis (blue curve) encodes the same information but focused on the analysis of a particular frequency. As an example, we see that the peak at almost 7 cycles/day in the data GLSP (red curve) is probably, from the blue curve, a spurious sidelobe created by the specific time sampling. This is also visible from the green curve, which shows that an alias peak appears at four rotations/days after the main peak.

From the considerations explained above, it is clear that a detection method based on the highest peak of the periodogram must evaluate the “statistical significance” of a given maximum peak’s height. One way to do this is to measure the probability of obtaining a value of the largest peak as high as the one observed in the data when there is only noise in the time series. This is investigated in the next Section.

4. Binary Candidates Selection Method

4.1. Statistical selection

For each window of search of each object, we computed the GLSP as described in Section 3.2 and obtained the value (say, v) of the highest peak.

A common proxy for the “statistical significance” of v is the p -value (see e.g. Efron (2010)), defined as follows. Let V be the random variable defined as the maximum value of the periodogram, conditional on the time sampling grid and error bars of the considered data. The p -value of v is the probability of obtaining a maximum peak value at least as large as v under the

squares) obtained when fitting a pure sinusoid at that frequency to a constant signal sampled like the data.

signal-absent hypothesis, with the same time sampling and noise error bars (denoted by $\mathcal{H}_0$). Formally this probability is

$$p(v) \equiv \Pr(V > v \mid \mathcal{H}_0) \quad (5)$$

In practice, the p -value $p(v)$ of a particular time series can be evaluated by Monte Carlo simulations by estimating empirically this probability as follows. We generate 10,000 simulated time series sampled with the same time sampling as the time series under investigation. Each time series is composed of a Gaussian noise consistent with the error bars plus a random constant (an offset drawn randomly from a zero-mean Laplacian distribution, which is consistent with our data, see Appendix A). The GLSPs of the 10,000 time series are computed and we count how often their highest peak has an equal or larger power than the one from the GLSP under investigation (v).

A p -value is computed in this way for each of the selected **30,030** times series. To be selected as a possible candidate, the time series must satisfy three conditions. The first condition is that the p -value estimated from the MC under $\mathcal{H}_0$ must be smaller than 0.05. The second condition is a check of the ‘robustness’ of the periodicity which we call “quality factor” below, and which also provides a method to estimate uncertainties for the amplitude and frequency associated with the main peak of the GLSP.

For this second condition, we perform MC simulations under the hypothesis that there is a sinusoidal signal in the data with the frequency and amplitude found from the GLSP of the candidate time series (plus noise with the considered error bars, plus an unknown offset, and with same time-sampling; we note this hypothesis $\widehat{\mathcal{H}}_1$). We then perform another series of 5,000 MC simulations of synthetic time series under $\widehat{\mathcal{H}}_1$.

A robust period detection should repeat nearly identically several times with different realisations of the synthetic data. To obtain the quality factor of the signal, denoted by Q below, we estimate the fraction of time series for which the GLSP highest peak is found ± 0.15 cycles/day around the injected frequency. Our second condition is that Q should be larger than 0.5, mean-

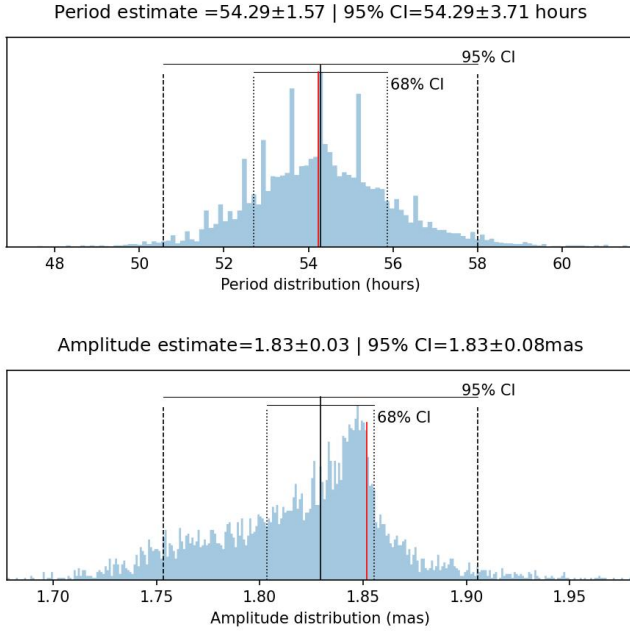


Fig. 5: Examples of uncertainties determination from MC simulations under $\widehat{\mathcal{H}}_1$. The top and bottom plots show in blue, respectively, the distribution of periods and amplitudes obtained from the best fit in each MC simulation. The red lines show the value estimated from the first GLSP run only on *Gaia* data, and the solid black line represents the median obtained from the distribution of amplitude and period values from the MC under $\widehat{\mathcal{H}}_1$. The dotted vertical lines show the 68% distribution interval while the dashed lines represent the 95% confidence interval of the distribution. The final results are given as the first estimate from the *Gaia* data (red line), and the uncertainty is the 95% interval. For instance, in this example, the final amplitude value is 1.85 ± 0.08 .

ing that the initially injected period should be retrieved more than half of the time in nominal noise and sampling conditions.

We underline that a large maximum peak caused by noise in the GLSP (i.e., a false alarm) will lead to a high value of the quality factor, because the wobbling amplitude estimated from the data will be large, so any strong but ‘fake’ detection will appear as robust concerning the Q analysis. In the opposite direction, a maximum peak with low amplitude will lead to a low estimated wobbling amplitude and a low value of the quality factor. Hence, while a large value of Q is not a guarantee that the detection is robust, the cross-analysis brought by the quality factor essentially provides a supplementary flag that some detections may not be robust (this will be further investigated in Sec. 4.2).

Finally, we turn to the third condition. An important aspect is that we are looking for astrometric binaries, which means that *Gaia* satellite would not have been able to observe the asteroid and the satellite separately. A wobble amplitude of 20 mas translates to a minimum separation of about 220 mas, which is above the *Gaia* resolution limit of about 200 mas. Hence, the third condition is that the wobble amplitude estimated $\widehat{A}_n$ must be smaller than 20 mas.

In summary, if the signal detected in the current window has a p -value $< 5\%$ as estimated from MC simulations under $\mathcal{H}_0$, a quality factor $Q > 0.5$ as estimated from MC simulations under $\widehat{\mathcal{H}}_1$ and estimated wobble amplitude smaller than 20 mas, then

the object is selected as a preliminary candidate and the values estimated in the current window are stored. The threshold of p -value $< 5\%$ is not very conservative since the expected number of false positives is about 1,500 (5% of **30,030**). In our case, the number of candidates that pass the triple test above is **3,038**. This number (larger than 1,500) can be explained by two reasons. First, indeed, by a population of true binaries that lead to smaller p -values. Second, by possible modelling errors (for instance, some un-modelled, low-order polynomial trends would lead to GLSP with larger peaks at low frequencies)³. However, as we will discuss in Section 4.2, the latter seems unlikely.

To obtain estimates of the uncertainties on period and amplitude, we use the results from the MC simulations under $\widehat{\mathcal{H}}_1$. In the case of mean period determination, we look for frequencies that are at most 0.25 cycles/day away from the best frequency found with the first GLSP and scan along the distribution to find the mean value, the 68% confidence interval, corresponding to the mean $\pm 1\sigma$ for a Gaussian distribution, and the 95% confidence interval. The value estimated from the first GLSP run is then selected as the wobble period and the 95% CI is the uncertainty on the period. The procedure is the same for the amplitude, but in this case, we limit the interval for amplitudes up to 2 mas away from the first amplitude estimate. Figure 5 shows an example of uncertainties determination for the period on the top plot and for the amplitude on the bottom plot.

If the object under the period search has more than one window of data, as discussed in Sec. 3.1, we repeat the same procedure described in all the other windows as well. Figure 6 shows a flowchart that summarizes the statistical selection processes discussed above.

4.2. Analysis of the detection performance of the statistical selection process

To evaluate the detection performance of our method, in this section, we make a general study based on the analysis of two cases. In the first case, there is indeed a signal in every time series analysed and we look at how good the method is at detecting and characterising it. In the second case, the time series have no signal and we examine how wrong the method can be in falsely selecting residuals with only noise.

4.2.1. Signal detection

In this analysis, we study the signal detection performance by grouping the simulated time series into classes of signal-to-noise ratio and looking at the results in terms of detections (at the right period or not), missed detections, associated estimated p -values and Q -factors. We use two signal-to-noise ratio definitions:

$$\text{“Base SNR”} : \text{SNR}_{\text{base}} \equiv A/\sigma \quad \text{and} \quad (6)$$

$$\text{“Post-fit SNR”} : \widehat{\text{SNR}} \equiv \widehat{A}/\widehat{\sigma} \quad , \quad (7)$$

where A is the true amplitude of the time series and σ is the nominal average uncertainty of the data set, $\widehat{A}$ is the amplitude estimate from the data time series and $\widehat{\sigma}$ the is the estimated average uncertainty of the data set.

³ While we do have some hints that a model with low-order polynomials could be more accurate than the model in Eq. (2), this would require to compute a much more computationally expensive Least Squares fitting at each frequency than the current GLSP. This improvement will be implemented in a subsequent version of our detection procedure.

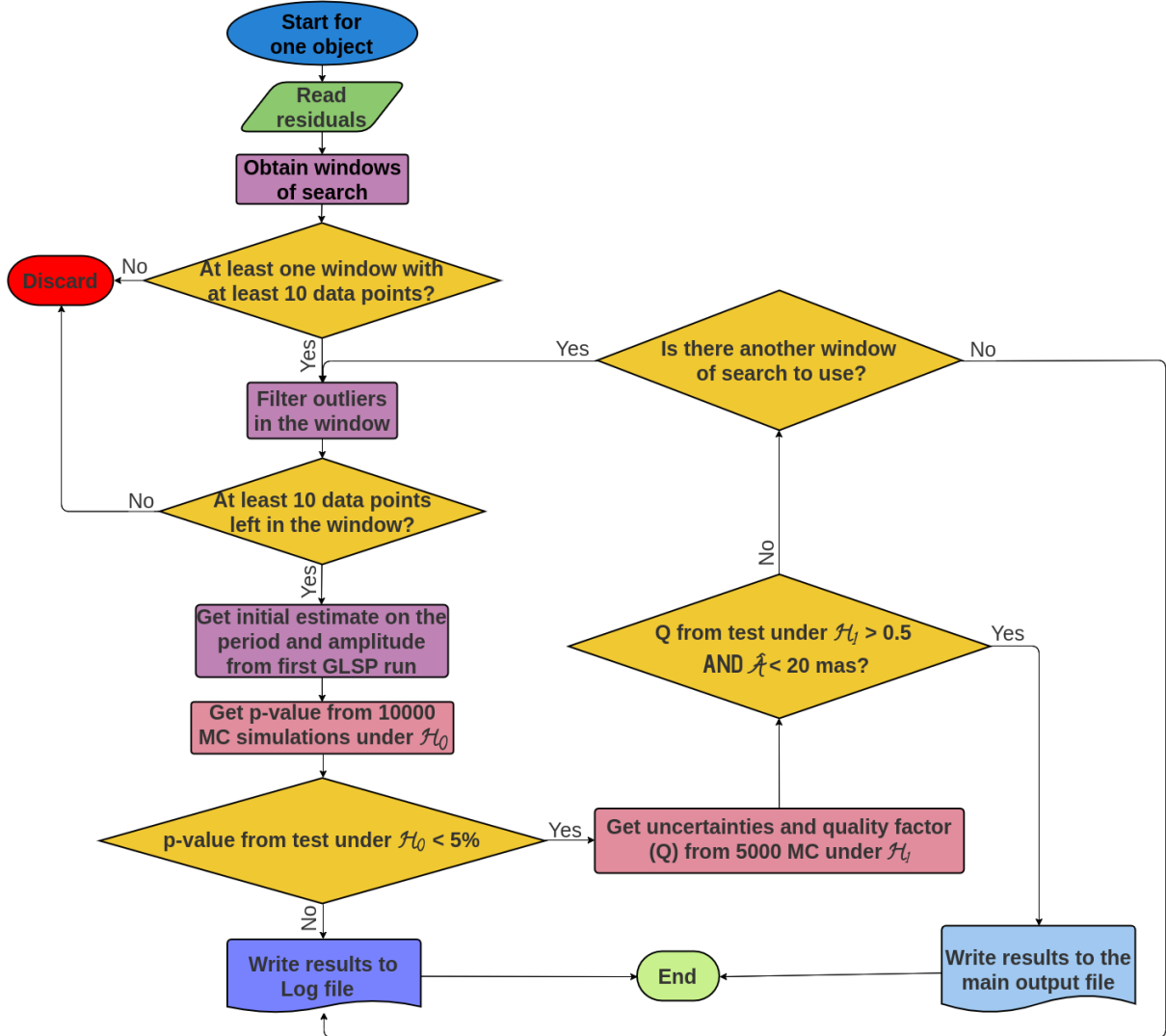
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Fig. 6: Flowchart showing the period search and statistical selection processes discussed in Sections 3 and 4. It represents part of the full detection process, which is coupled with physical characterisation tests that will be discussed in the following sections.

To obtain the performance analysis we perform the period search and selection method shown in Fig. 6 for 6 different SNR_{base} values, with Monte Carlo simulations based on 1,000 time series of synthetic AL residual. First, we choose a set of different values of SNR_{base} between 0.5 and 3.0. We create each set of synthetic data from a sinusoid with a known amplitude A of 1 mas, a period of 23 hours (a frequency close to but not exactly 1 cycle/day to avoid possible bias) and a random phase between 0 and 2π . The nominal average noise σ for each set of synthetic samples is estimated using Eq. (6).

For the simulations of the time series, we draw 12 observation epochs, randomly distributed in 6 days. The small number of points, the randomness in the data and the time sampling are aimed not only at representing the data from *Gaia*, which is usually modestly sampled over a few days but also at providing conservative results that cover most of the non-ideal cases.

For each time series, the actual standard deviations of the errors σ_n are obtained by a random perturbation of σ (using a zero-mean, normal distribution of std 0.8; this setting is aimed at creating some scatter in the actual SNRs within each SNR class), and we add one random Laplacian offset as described in Ap-

pendix A. Then, for each one of the 6,000 synthetic time series simulated in this way, we run the statistical selection (Section 4.1).

Fig. 7 shows the results for the (p, Q) pairs of 6,000 time series simulated. We notice that, as expected, for low values of SNR_{base} the parameters p and Q tend to be more scattered and present less correlation between themselves. But for higher SNR_{base} values, the couples (p, Q) tend to cluster around the “best conditions” represented by very low p -values and high Q .

Intuitively, the larger the SNR_{base} of a signal the easier it would be for the method to detect it. It is also expected that very noisy signals hamper the period fitting and provide wrong detections more often, and our results follow that behaviour.

For time series with SNR_{base} close to 0.5, the method achieves 11.3% of detections, of which 69% have wrong periods. For the SNR_{base} class of 1.0, the detections represent 56% and about half present wrong periods. For the SNR_{base} classes larger than 2.0, the method detects more than 93% of the signals with a low rate of wrong detections.

It is also interesting to check the distribution of the quality factor (Q) and the p -value depending on the SNR_{base} , as pre-

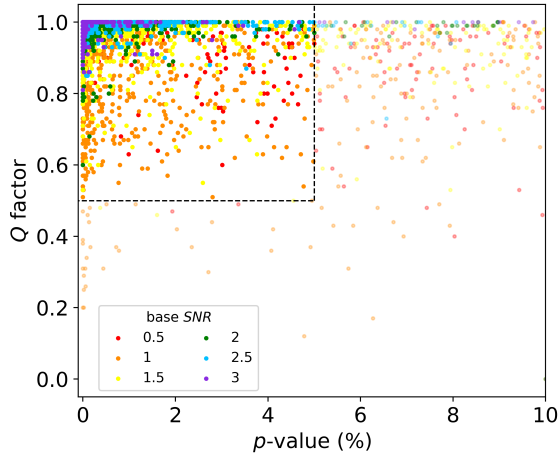


Fig. 7: Distribution of pairs (p, Q) for each one of the 6,000 sets of synthetic data simulated. The partially transparent dots represent the cases where the detections do not meet the requirements and were disqualified, while the remaining dots represent the detections selected. From the 6,000 simulations, 1,303 of them have $p\text{-value} > 0.1$. Hence, their Q factors were not calculated and the corresponding points are not shown in this plot.

sented in Fig. 8. It shows the distribution of best periods fitted on the top plots, the distribution of Q in the plots in the middle and the p -value distributions on the bottom plots for each different class of SNR_{base} studied. As discussed before, we notice that for small SNR_{base} there is a significant amount of detections with periods far from the real value, represented by the dotted black line. Also, the corresponding distribution of Q shows that the quality of the detection tends to be mostly below 0.8, much smaller than for larger values of SNR_{base} where Q is usually closer to 1.0. Similar behaviour can also be seen in the p -value distributions where the higher the SNR_{base} , the larger the concentration of results with small p -values.

The p -value is usually the only parameter used in the selection of detections. In fact, for $SNR_{\text{base}} > 1$, we find that almost all missed detections have $Q > 0.5$, so the p -value is the parameter ruling the selection and Q has almost no influence in the selection process. However, for $SNR_{\text{base}} \leq 1$ there are many cases with p -values smaller than 5% where Q is used to filter the weak detections, as seen in Fig. 7.

Of course, when applying the detection method to real *Gaia* data, we can only estimate the signal-to-noise ratio based on the sinusoidal fit from GLSP. This is the reason why, in addition to the analysis of the detection performance based on the base SNR_{base} values, it is also interesting to study the results based on the post-fit SNR ($\widehat{SNR}$), which is indeed different from the SNR_{base} . As shown in Fig. 9 we see that the number of detections increases for the largest values of SNR_{base} , as in Table 1.

By combining all the results from the 6,000 time series, we can simulate the situation where we do not know the original parameters of the time series and have only the post-fit signal-to-noise ratio. Then, we separate them in intervals of mean $\widehat{SNR} \pm 0.1$ and check the statistics, as it was made previously for the SNR_{base} classes. The results are presented in Table 2.

From the comparison between the analysis based on SNR_{base} classes presented previously, and the one based on the post-fit $\widehat{SNR}$, these results indicate that there are no major differences in

the statistics of detections between both approaches, especially for $\widehat{SNR} \geq 1.5$.

It is interesting to note from these results that in the scenario where there are signals in all of the time series analysed, but we do not know the SNR_{base} , $\widehat{SNR} \leq 1$ lead to p -values and Q factors that often fail to pass the selection test. Meanwhile, for $\widehat{SNR} \geq 2$ we find more than 85% of the detections around the correct period with a rate of wrong/correct smaller than 10% and we miss less than 3% of the detections.

We conclude that a $\widehat{SNR}$ of about 1 appears to be a limit for the detection regime in this setting. For increasingly stronger signals, with larger $\widehat{SNR}$, we have an increasingly smaller rate of wrong detections. The method succeeds accordingly at classifying the sample as detection, at recovering the correct period in the data and at providing a good approximation of the real SNR .

4.2.2. Noise-only scenario

The purpose of this analysis is to understand how the method performs when there is no signal in the data and to assess its robustness in handling data with no wobble at all.

For that purpose, we generated 6,000 sets of simulated AL residuals by replicating the error bars and time sampling of original AL residuals from *Gaia* asteroids. These synthetic noisy time series were generated by drawing random samples with Gaussian noise perturbation corresponding to the target error bars and we added in each time series a random offset consistent with the *Gaia* time series, cf Appendix A.

As discussed in Sec. 4.1, with a p -value threshold of 0.05 it is by definition expected that 5% of the time series are selected (on average) if none of the data present a real signal. Our results showed that in the considered noise-only scenario, the statistical selection process selected as detections about 4.8% of the time series analysed.

The left plot in Fig. 10 shows the distribution of (p, Q) pairs for the 609 time series with $p\text{-value} < 0.1$. The remaining 5,391 time series present $p\text{-value} > 0.1$ and therefore their Q was not calculated. We see that the resulting dispersion in the (p, Q) plane is similar to that observed in Fig. 7 for classes of $SNR_{\text{base}} \leq 1$. This is in contrast with classes of larger SNR values for which the points tend to cluster around the top left corner.

Turning to the right panel of Fig. 10, we see that noise-only data lead to post-fit SNR values distributed around $\widehat{SNR} \approx 1$, with few cases having $\widehat{SNR} \geq 2$. As expected, this distribution is compatible with the lowest SNR classes of Fig. 9.

In a nutshell, we conclude from this two-fold performance study that, when a wobble is indeed present, our statistical selection process behaves as expected and increasingly succeeds at retrieving this wobble as its amplitude increases. In the situation when there is no wobble, the wrong detection rate is controlled and does not exceed the prescribed value (set to 5% here).

Finally, the SNR value of 1 appears to be a turning point in the detection regime, post-fit SNR values larger than ≈ 2 being a serious hint of the presence of a population of real wobbles⁴.

⁴ Indeed, the detectability of a signal depends also on the time sampling. Two wobbles with the same SNR but sampled differently will in general have different p -values and probabilities of detection. In our simulations, the time sampling of the simulations is generated in agreement with the *Gaia* sampling of the considered AL residuals. Our results are averaged over a large number of different sampling grids. Hence, the frontier of a unit SNR should not be taken at face value but reflects a global behaviour corresponding to the considered sampling conditions.

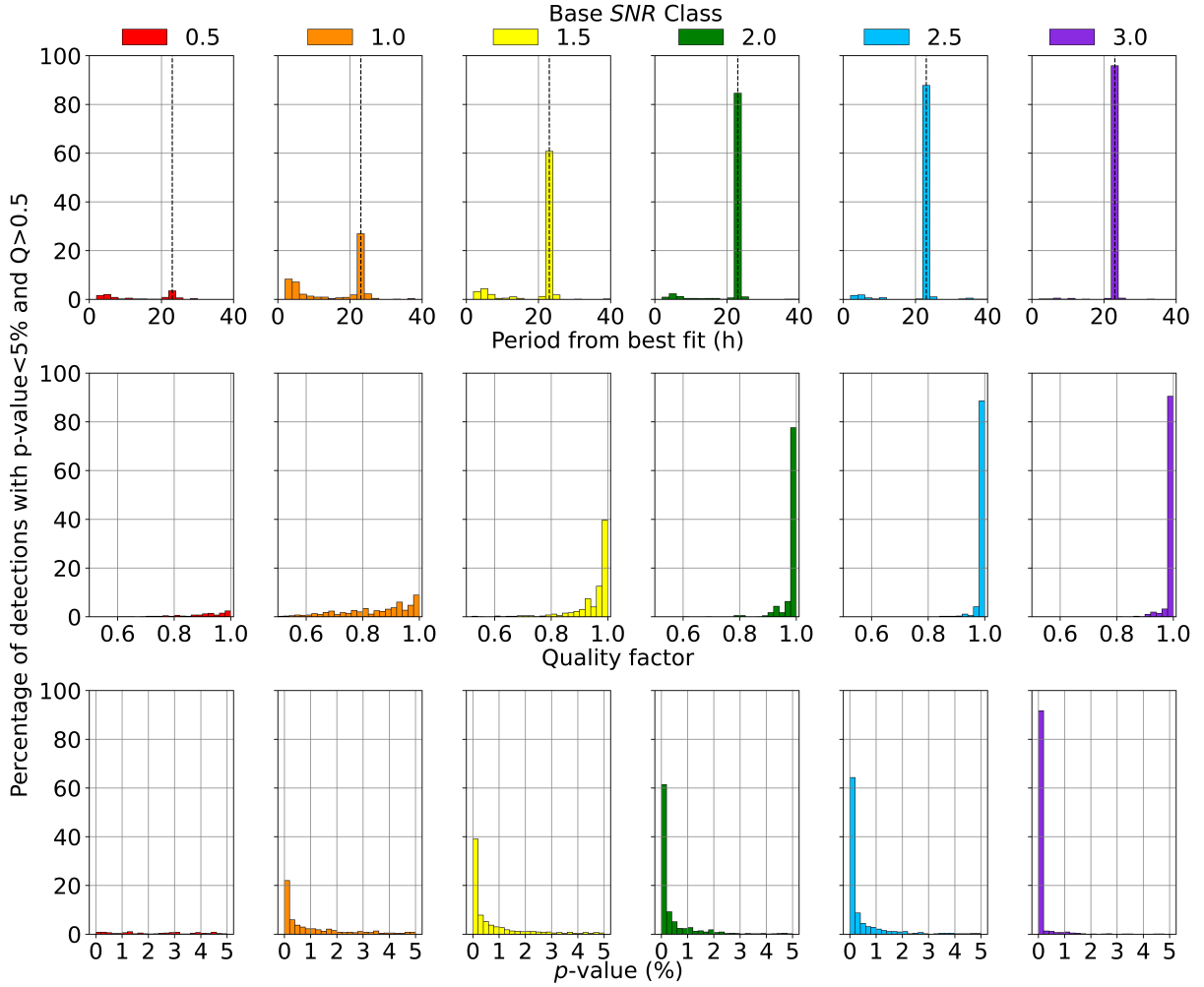
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Fig. 8: Distribution of periods from best fit (top row), quality factors (center row), and p -values (bottom row) as percentages of the detections selected with p -value < 5% and $Q > 0.5$. The different coloured bars represent the different classes of SNR_{base} values explored. The dotted line at 23 hours represents the nominal (true) period of the injected signal.

4.3. Period search results overview

In this Section, we apply the detection method to the AL residuals data set. Figure 11 visually illustrates the results of the processes of selection and parameters determination for the case of an object that satisfies the requirements (at least one window with 10 observations in less than 10 days, p -value < 0.05, $Q > 0.5$ and estimated wobble amplitude $\hat{A}$ smaller than 20 mas) and was selected as a possible candidate by the period search. In this case, for (3457) Arnenordheim, we have a window with 17 observations spread over 2.75 days (as shown in Fig. 3, right panel). The periodogram shows a large peak (Fig. 11 top left) that provides the best fit in the observations with a period of 45.95h (Fig. 11 top right). The MC analysis leads to a very low p -value (< 0.001%, Fig. 11 bottom left) and a quality factor Q of 1 (Fig. 11 bottom right).

The distribution of estimated periods and wobble amplitudes $\hat{A}$ for the 30,030 candidates (Fig. 12) shows that small amplitudes are preferentially discarded, as expected since the signal-to-noise ratio tends to be small, but the general distribution remains overall the same. We notice a kind of “tail” in the distribution for the large period and amplitude values, and they are

mostly not selected as detections. This phenomenon might be caused by unmodeled low-frequency trends (see Sec. 4.1).

It is also noticeable in Fig. 12 a concentration of detections around 3, 4, 6 and 12 hours with larger amplitudes, even though there is no over-representation of such periods. That happens due to the typical frequencies present in the *Gaia* scanning law (time interval between the two FOVs, rotation period of 6h, precession of about 2 months, and combination of them). In some cases, the sampling of the data set has a dominant effect on the period search causing the GLSP to find the best period at, or very close to, values of 2, 4, 6 and 8 cycles/day. However, some of the detections found at such values might be real, so we leave at the next selection steps the task of cleaning the spurious detections that are not physically meaningful. In future improvements of the method, we intend to account for this effect. Finally, we note that the apparent vertical alignment of points for small values of $\hat{A}$ is due to the bin size in the determination of the mean value estimate, which is more noticeable due to the logarithmic scale of the plot.

We find that 83.8% of the windows of data analysed lead to non-detections due to a p -value larger than the 5% threshold and about 6.6% are disqualified because $Q < 0.5$ even though

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SNR_{base}	Detections	Detections around correct period	Detections with wrong period	Missed detections	Wrong/Correct period detection rate
0.5	11.30	3.50	7.80	19.60	69.0
1.0	56.10	26.90	29.20	13.80	52.0
1.5	76.88	60.76	16.12	11.81	21.0
2.0	93.30	84.60	8.70	5.10	9.3
2.5	95.20	87.80	7.40	3.00	7.8
3.0	98.40	95.90	2.50	1.30	2.5

Table 1: Results for each class of SNR_{base} studied. The first column represents the base signal-to-noise ratio used. The second column shows the total percentage of detections in the sample. The third column shows the percentage of detections in which the best period fit is up to one hour away from the nominal period chosen. The fourth column presents the percentage of detections where the period is further than 1 hour from the nominal value, complementary to the previous column. The fifth column shows the percentage of missed detections because they did not pass the selection tests, but the period found is close to the nominal period. The last column shows the fraction of the detections with wrong periods concerning the total number of detections, representing the probability of wrong detection.

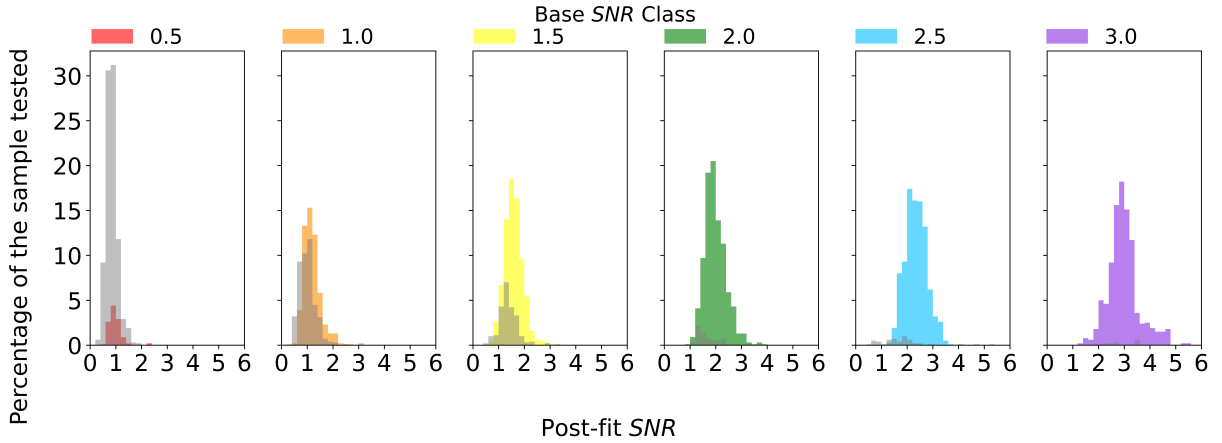


Fig. 9: Distribution of time series selected as detections (coloured bars) and discarded (grey) as a function of the post-fit $\widehat{SNR}$, for the six different SNR_{base} classes explored.

$\widehat{SNR}$	Detections	Detections around correct period	Detections with wrong period	Missed detections	Wrong/Correct period detection rate
0.5	11.61	2.90	8.71	17.10	75.0
1.0	43.25	20.68	22.56	16.75	52.2
1.5	76.56	56.64	19.92	11.62	26.0
2.0	94.58	85.85	8.73	2.83	9.2
2.5	98.15	94.14	4.01	1.54	4.1
3.0	99.15	94.87	4.27	0.00	4.3

Table 2: Same as Table 1, but with the analysis based on the $\widehat{SNR}$.

the p -value is within the limit. Eventually, only 9.6% of the sets of AL residuals comply with the requirements and are selected as possible binary candidates by the statistical selection, which represents **3,038** asteroids, of which 40 have estimates from different time windows of observations.

Some results from different windows are very similar, but most of them show considerably divergent values. At this point, we are not able to decide which window has the most physically meaningful results. Therefore, an asteroid that has been estimated with different periods and amplitudes in different windows at this stage will have each couple of possible solutions (period, amplitude) considered in the next stage, where the least physically consistent results will be rejected.

4.4. Selection based on physical properties

For the **3,038** *Gaia* asteroids whose data passed the statistical detection test above, we move forward to check if the measured wobbling is compatible with the fundamental physical properties expected for an orbiting satellite. Under the hypothesis that the periodic signals correspond to the orbital period, we can exploit known properties measured by other surveys, such as the object size, to infer the range of size ratios and densities that could generate the observed signal. Density, in particular, should be within acceptable ranges, and compatible with the expected mineralogy for a corresponding spectral type.

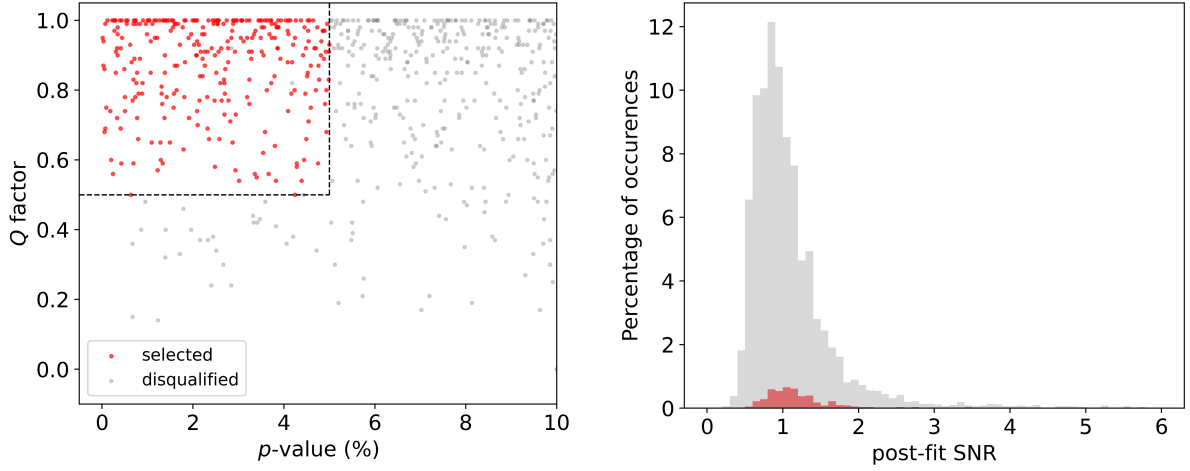
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Fig. 10: The left plot shows the distribution of pairs (p, Q) for the noise-only time series simulated. 5,391 of the cases have $p\text{-value} > 0.1$ (for these cases the Q factors were not calculated and the corresponding points are thus not shown). The grey dots represent the cases where the data was disqualified as a detection (cases for which $p > 0.05$, $Q < 0.5$, or both) and the red dots represent the detections. The two grey points in the top left square are detections discarded due to $\hat{A} > 20$ mas. The right plot presents the post-fit signal-to-noise ratio distribution for the pairs in the left plot.

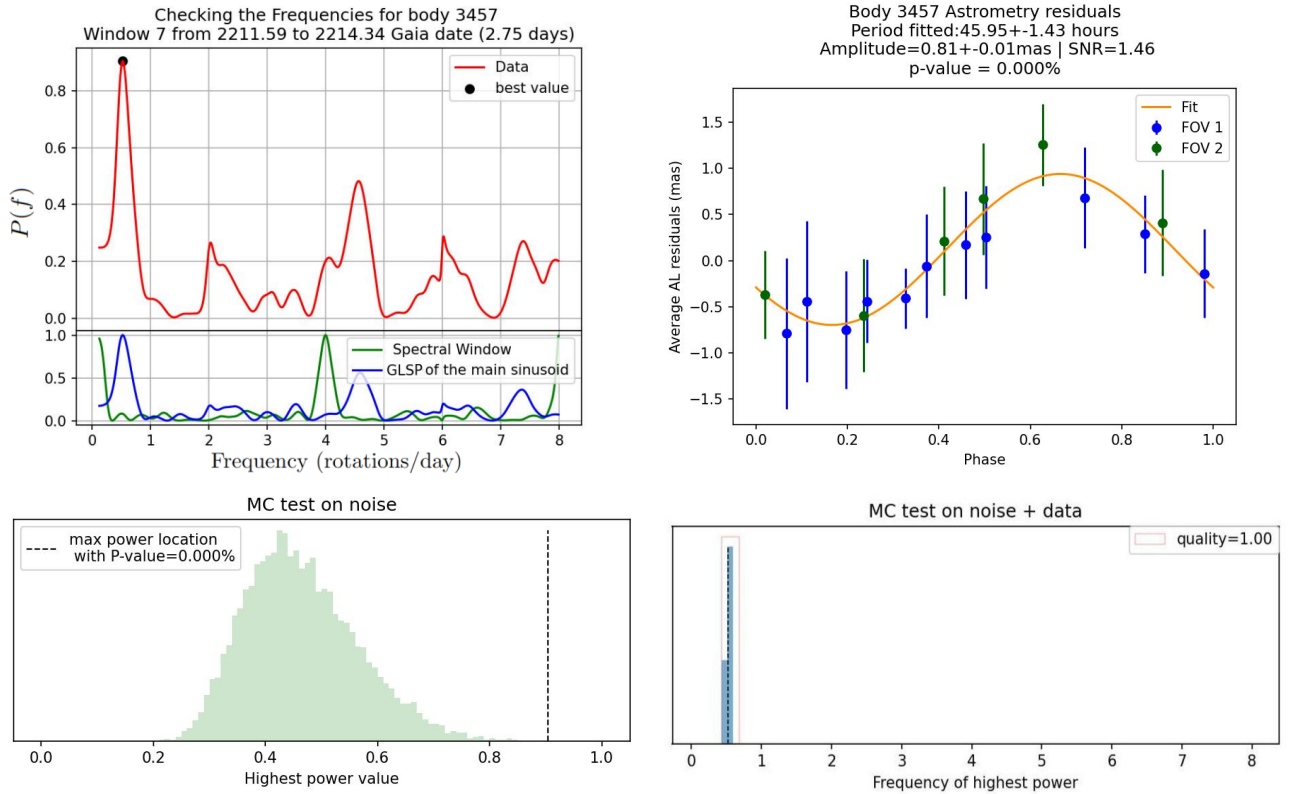


Fig. 11: Visualisation of the output of the main steps of the selection process in the period search for one candidate example ((3457) Arnenordheim). The top left plot shows the periodogram from the fitting of the 17 observations in the window. The peak represents a period of 45.95h and the best fit is shown in the phased data in the top right plot. The distribution of data points not phased is shown right plot in Fig. 3. The bottom left plot shows the empirical distribution of GLSP power V (maximum value of the GLSP under $\mathcal{H}_0$) and the vertical dashed line shows the position of the value of v , the power of the peak from the periodogram with the real data, with $p(v) < 0.001\%$. Finally, the bottom right plot shows the distribution of best frequencies from the 5,000 MC simulations under $\hat{\mathcal{H}}_1$. Here, this distribution tends to accumulate around the originally estimated frequency, showing that this detection is robust (here, Q is close to 1.)

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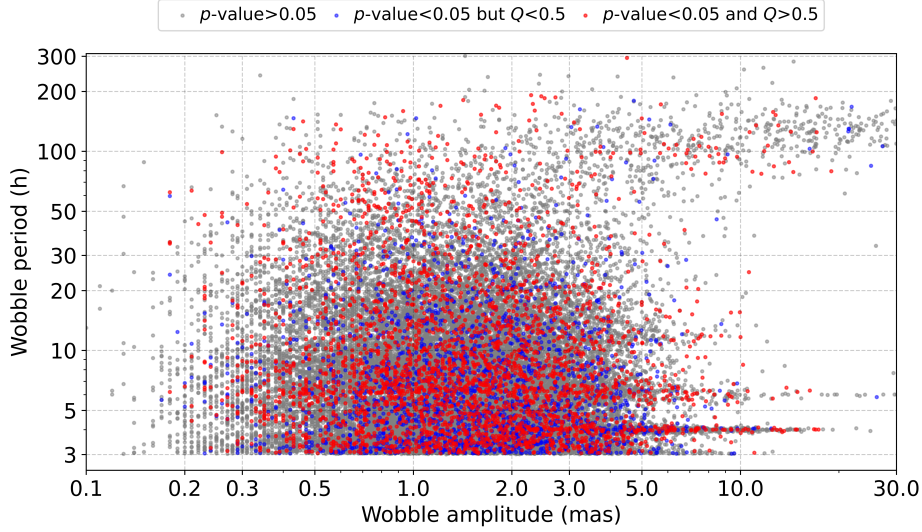


Fig. 12: Distribution of estimated wobble amplitudes and periods obtained from the period search for all objects. In grey are the time series disqualified due to a p -value > 0.05 , in blue are the cases disqualified because $Q < 0.5$ but with p -value within the limit of 0.05, and in red are the cases selected as binary candidates from the period search for complying with p -value < 0.05 and $Q > 0.5$.

We start with Kepler's 3rd law of planetary motion:

$$\frac{T^2}{a^3} = \frac{4\pi^2}{M_{\text{total}}G}, \quad (8)$$

where M_{total} is the total mass of the studied system ($M_1 + M_2$), T is the orbital period of the secondary body around the primary, which we assume to be the same as the wobbling period, and G is the gravitational constant. We manipulate the equation to express it as a function of the mass ratio of the system $q = \frac{M_2}{M_1} = \frac{D_2^3}{D_1^3}$, the diameters of the primary and secondary component (D_1 and D_2 , respectively), and the bulk density ρ .

Furthermore, we also consider that the currently observed diameter corresponds to a sphere of surface brightness equivalent to the sum of the binary components, $D^2 = D_1^2 + D_2^2$. Hence, the total mass of the system can be written as:

$$M_{\text{total}} = \frac{\rho\pi}{6} \frac{D^3}{(1 + q^{2/3})^{3/2}} (1 + q). \quad (9)$$

Finally, substituting Eqs. (9) and (1) into Eq. (8) and with some manipulations, we obtain a relation describing the density ρ as a function of the mass ratio q :

$$\rho = \frac{24\pi\alpha^3}{GT^2D^3} \left| \frac{(1 + q^{2/3})^{3/2}(1 + q)^2}{q^2(q^{1/3} - 1)^3} \right|, \quad 0 < q < 1. \quad (10)$$

By this expression, the dependency of the density from the mass ratio q can be evaluated, by assuming an estimation of D , once T and α are measured from the astrometric wobbling.

We retrieve D from literature⁵, along with the associated uncertainty. If SsODNet does not provide the diameter for a given object, we estimate it from the absolute magnitude H by taking the mean diameter for the geometric albedos p_v , spanning the interval $[0.06, 0.2]$. We assume a standard deviation of 15% for

convenience, considering that without this assumption the errors in the diameter estimates are larger than 50%. This restrictive choice is partially compensated by the generous density interval that is allowed, as explained in the following.

While T is a direct result of our signal analysis, the measured amplitude α is only a minimum value, due to the unknown projection factor of the real wobble in the AL direction. In this respect then, having fixed all other parameters, Eq. (10) provides a *minimum* density as a function of q .

The Eq. (10), as shown in Fig. 13, is a concave function with a minimum corresponding to the maximum wobbling amplitude in Eq. (1). This minimum represents the smallest ρ of the system compatible with the observed wobbling. The uncertainties are obtained with the linear propagation of the errors in D , T and α .

For a first selection, we consider a large density range $\rho \in [0.3, 7] \text{ g/cm}^3$. We are interested in selecting the possible ranges of mass ratio q corresponding to densities in this interval. Therefore, when the minimum of the density function is $< 0.3 \text{ g/cm}^3$, we obtain two separated intervals delimited by 4 different values of mass ratio ($(q_{\text{min}1}, q_{\text{max}1})$ and $(q_{\text{min}2}, q_{\text{max}2})$). From them, and the associated values of ρ , the corresponding values of the total mass can be computed and used in Eq. 8 to derive two different intervals of possible separation of the binary ($(s_{\text{max}1}, s_{\text{min}1})$ and $(s_{\text{min}2}, s_{\text{max}2})$). This is the case of (7616) Sadako in Fig. 13.

In cases where the minimum density estimate is never smaller than the inferior limit, as for (6261) Chione, we get a single interval of q and possible separations. Eventually, if the function has a minimum value larger than the adopted upper threshold, the wobble signature is considered not compatible with a binary object as this would require an excessive density.

By adopting the density threshold mentioned above, 934 objects are selected and their possible ranges of q and s have been computed.

A further step consists in considering the smallest separation, for each candidate, compatible with an orbiting companion. We find that for some of the objects the range of separations par-

⁵ SsODNet(<https://ssp.imcce.fr/webservices/ssodnet>) service through rocks4 python-interface (<https://github.com/maxmahlke/rocks>). (Berthier et al. 2022).

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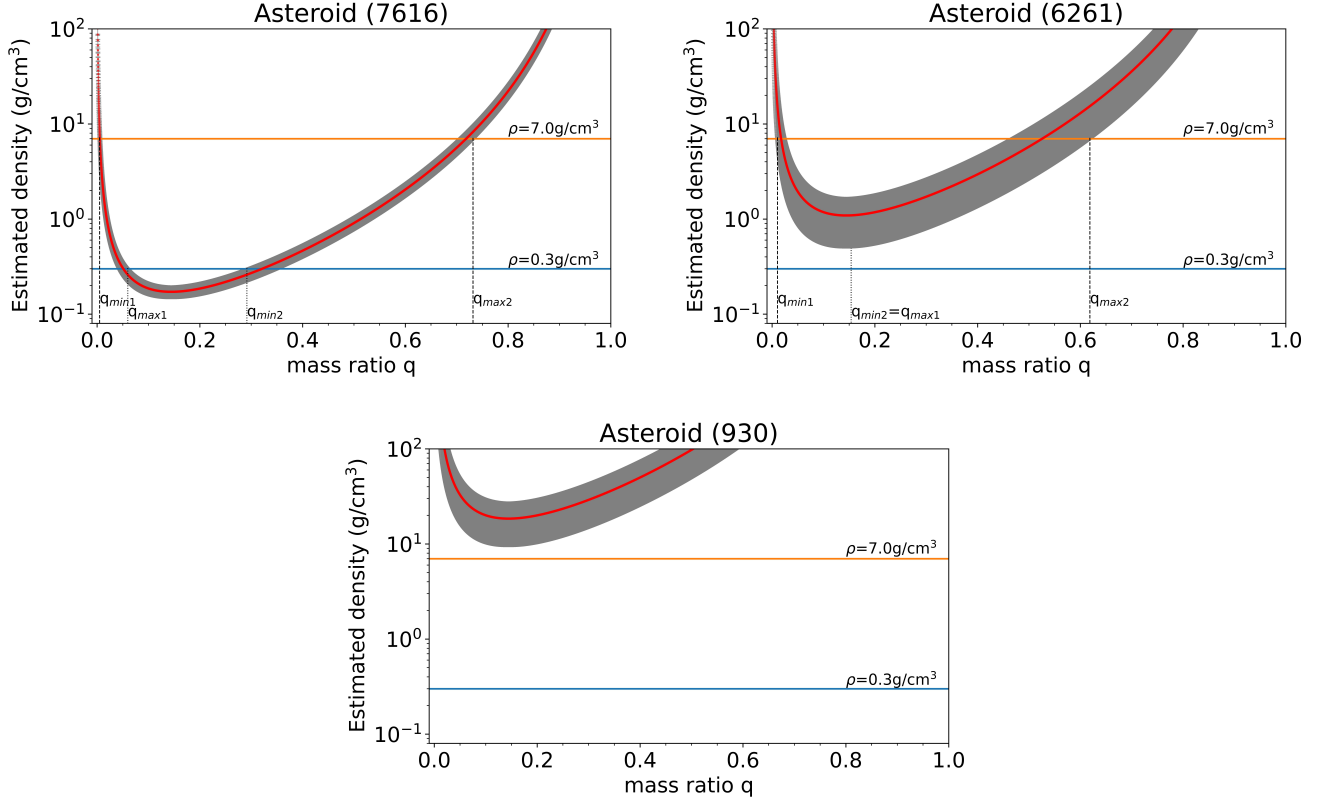


Fig. 13: Examples of the bulk density ρ as a function of the mass ratio q for two asteroids, (7616) Sadako (top left) and (6261) Chione (top right). The red line indicates the nominal value. Shown in grey is the error range on the density. The blue and orange horizontal lines represent physically reasonable limits. q_{min1} , q_{max1} , q_{min2} and q_{max2} mark the corresponding extremes of the mass ratio values. The bottom plot shows the case for (930) Westphalia, eliminated in the density filtering because the minimum estimated density is larger than the chosen range of bulk density.

tially overlaps with the Roche limit⁶, computed by assuming the same density for the two components. Binary systems inside the Roche limit are unlikely to exist, and the detected wobble could instead be caused by a very irregular shape. Of course, more accurate physical data, in particular diameter measurements, could change the results for some objects and put them beyond the Roche limit. To be conservative, for this first search, we have decided to reject candidates that have separation intervals overlapping, even partially, with the Roche limit. With this selection, we remain with 362 wobble measurements for **358** objects (table in Annexe B).

4.5. Constraints from taxonomy

The average density value for each taxonomic class can help to further constrain the physical properties of objects in our selection. We retrieved the taxonomic class for all objects in the list of preliminary candidates using SsODNet. Of the **358** candidates selected from the previous steps, 264 have their classes determined, corresponding to one of the complexes for which an average density is provided in Carry (2012).

By using the average density for the taxonomic class, we can repeat the analysis illustrated in Sect., recompute the permitted intervals of possible physical parameters, and refine the selection of the sample. We reached a total of **156** candidates.

Also, since large real wobbles will tend to produce high $\widehat{SNR}$ (cf Section 4.2) we flag as *best candidates* those with $\widehat{SNR} > 1$.

The objects of our sample on which taxonomy-derived density constraints are applied are presented in Fig. 14, which shows the estimated radius of the primary as a function of the allowed separations (in units of the radius of the primary) for the **156** objects. The purple and pink points represent the first and second intervals of possible mass ratio values. Those with dark borders are the best candidates with $\widehat{SNR} > 1$, and the points with grey borders are the candidates with $\widehat{SNR} < 1$ that are not in the list of the best cases but still passed through all the filtering steps.

5. The final sample of candidate binary asteroids

In the list of **358** asteroids explored from *Gaia* DR3, there were 80 known binaries.

The total outcome of **358** objects from this first search of astrometric binary candidates appears in Appendix B. It includes 5 known binaries, **67** of which (highlighted) present results with the density constrained by taxonomy and $\widehat{SNR} > 1$.

Table 3 summarises the number of candidates after each step of our selection process. We select the **30,030** asteroids in DR3 with consecutive observations in a short time span. From the statistical selection, we obtained **3,038** preliminary candidates that presented $p\text{-value} < 0.05$ and $Q > 0.5$. The validation on the physical ground and the selection based on known taxonomic

⁶ $d_{\text{Roche}} = 2.44 R_{\text{primary}} (\rho_{\text{primary}} / \rho_{\text{secondary}})^{1/3}$

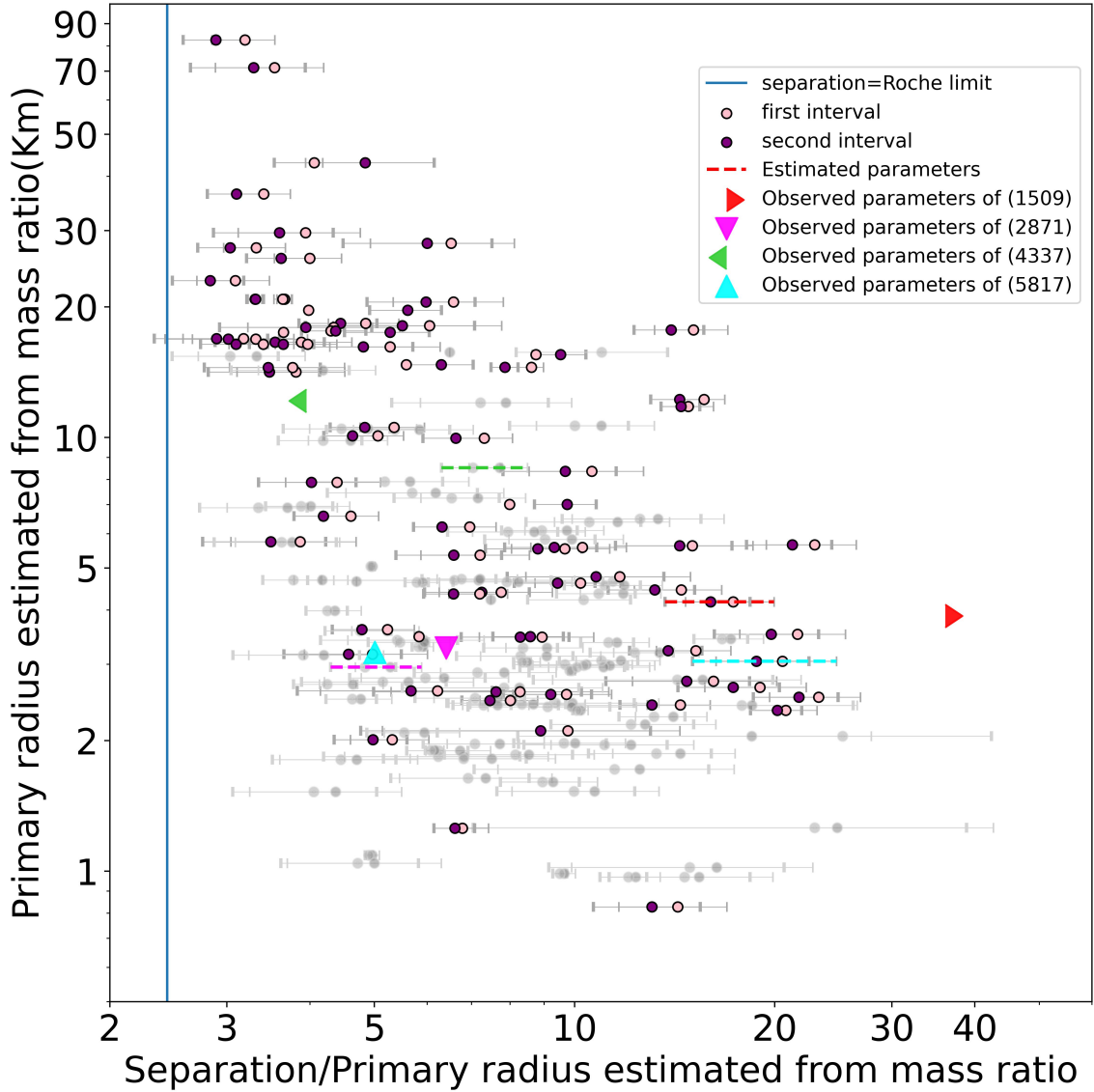


Fig. 14: Plot of the radius of the primary as a function of the separation intervals normalised with the Roche limit for fluid satellites, for the sample of **156** asteroids with known taxonomy. The circles represent the mean value of the first and second mass ratio intervals estimated. The coloured circles with dark borders are the objects from the taxonomic filtering with $\widehat{SNR} > 1$, and the grey circles are those with $\widehat{SNR} < 1$. The four coloured triangles represent the expected parameters of four known binary asteroids as described in the legend, and the dashed lines with the same colours are the intervals we estimate. The solid blue vertical line is located at $x=2.44$, which is the position where the separation is equal to the Roche limit.

type further restricted this list to **156** objects presenting characteristics compatible with binary systems. Most of them have an estimated $\widehat{SNR} < 1$, as the regime of scarceness of the data and potentially low wobble amplitudes make detectability difficult. Therefore, we can consider that those with $\widehat{SNR} > 1$ among the **156**, are the best characterised. The distribution of their parameters concerning the statistical thresholds of period determination is shown in Fig. 15.

We notice that the method seems to favour the selection of objects presenting periods longer than 10 hours, which is perhaps the sign that high frequencies not captured by the constant plus sinusoid model of the GLSP are present in the time series.

By filtering the physically meaningful candidates we eliminate most of the cases with p -values $> 2\%$ and $Q < 0.9$ and the best candidates are mostly those with very low p -value and Q close to 1. The comparison between Fig. 16 and Fig. 10, showing the heavier right tail of the $\widehat{SNR}$ distribution obtained from *Gaia* data, further strengthen the evidence that our candidates are indeed binary asteroids.

Two of the best candidates in the list, (2219) Mannucci and (542) Susannahave, present matching wobble periods from two different time windows, separated in time by weeks or months. At such large intervals, the orientation of the wobbling motion relative to the scan direction can be different (as confirmed by the

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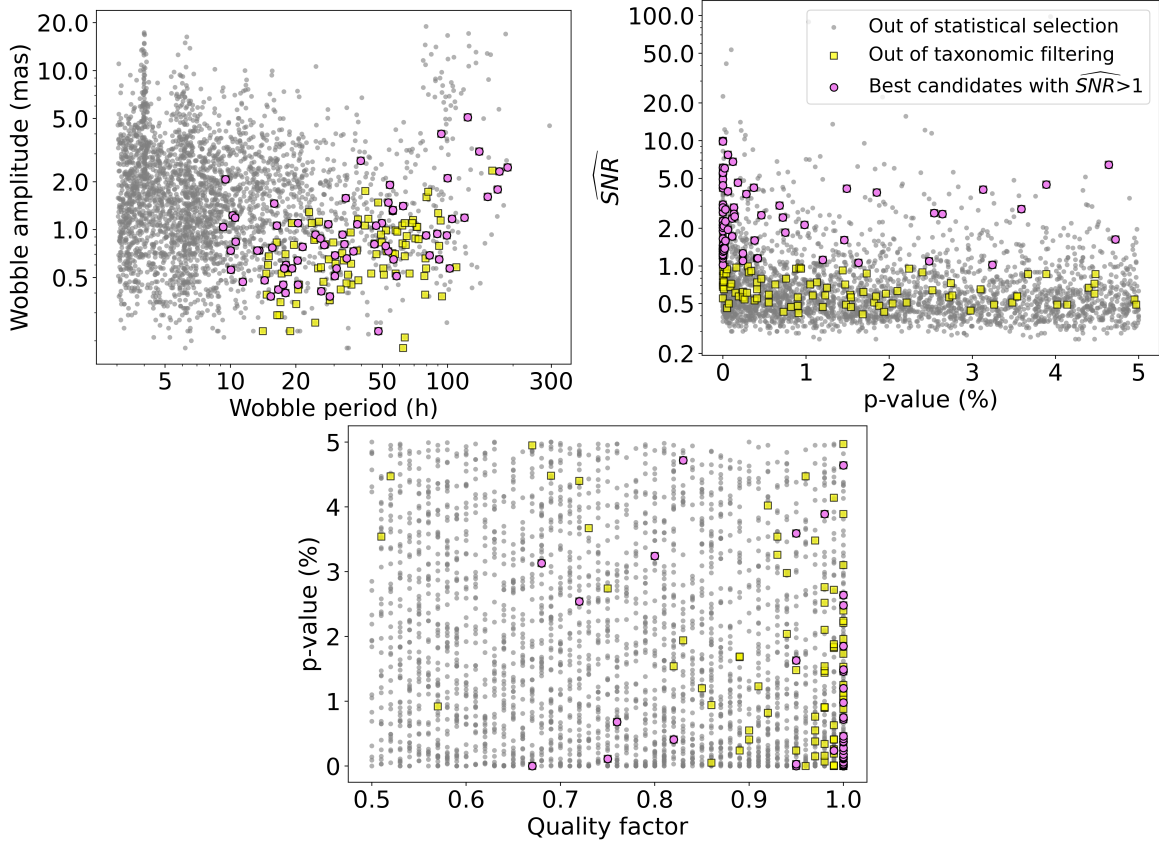


Fig. 15: Distribution of estimated wobble period versus wobble amplitude (top left), $\widehat{SNR} > 1$ vs p -value (top right) and p -value vs quality factor (bottom) for the **3,038** objects obtained from the statistical selection in grey, the **156** objects that survived the taxonomic filtering in blue, and in purple the **67** best candidates that passed all tests and have $\widehat{SNR} > 1$.

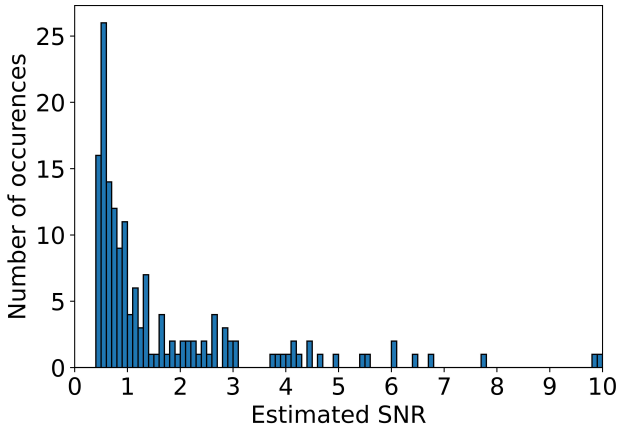


Fig. 16: Distribution of $\widehat{SNR}$ for our list of **156** binary candidates selected from the taxonomic filtering. The **67** best candidates are those with $\widehat{SNR} > 1$

different wobble amplitude), thus making these measurements independent. The fact that the two estimated wobble periods of each object match is another sign that our method of period search is rather robust.

The bodies selected as best binary candidates, including the known binary asteroids, are in large majority main-belt asteroids (Inner MB: 11, Middle MB: 26, Outer MB: 22), but 3 Phocaea, 3 Mars-Crosser, 2 Hungaria, 1 NEA Amor and 1 Trojan are also present. All of our best candidates present separations < 200 mas, below the limit at which the onboard Video Processing Unit of *Gaia* treats sources separately.

5.1. Known binaries

In Fig. 14 4 known binaries are highlighted: (1509) Escarglona, (5817) Robertfrazier, (2871) Schober and (4337) Arcibo, the first two with $\widehat{SNR} > 1$. The coloured dashed lines represent the parameter range of these objects from our analysis and the triangles with the same colours are the values that we consider for reference, extracted from the Johnston's Archive Website⁷.

Such a small number of known binaries is not unexpected, since our filtering and statistical validation reduce a large sample to a very small population. For each binary, the probability of showing an astrometric signature in *Gaia* DR3 is not very high, as it requires the appropriate orientation of the wobble motion concerning the scan motion, during the periods of consecutive observations.

The four remaining binaries offer in principle the possibility of validation of our approach, but in practice, other limitations

⁷ See <https://www.johnstonsarchive.net/astro/asteroidmoons.html> and references therein

appear. It is not possible to exploit Esclangona, whose satellite has a reported orbital period of 23 days, too long concerning the time span of our search (we find a possible periodicity of 5.15 days). For Robertfrazier, we find a wobble period >5 times the reported one, but with a large uncertainty.

Interestingly, however, for both these wrong matches the apparent wobble signal is strong, with a $\overline{SNR}$ of 6.09 for Esclangona, and 2.64 for Robertfrazier, and the wobble amplitude is high, especially for Esclangona. Another satellite in the system could be present, and future *Gaia* astrometry will probably help to clarify these detections. In both cases, the interest in having these objects selected by our procedure remains.

For Schober, we find solutions from two different time windows of observation, with wobble periods of 20 ± 4 hours and 50 ± 11 hours. Both of them are compatible with the archive value (42.470 ± 0.019 hours): the first can be considered an alias emerging from the data at about double the frequency, while the second results in intervals of separation that overlap partially with the Roche limit, so it was rejected by the filtering.

For Arecibo, the expected orbital period of the satellite is within the uncertainty of our wobble period estimate. In this case, the difference between the expected and estimated parameters is due to differences in density values. Our procedure considers Arecibo as an S-type whose average density is $2.7 \pm 0.69 \text{ g/cm}^3$ (Carry 2012). This is in contradiction with Tanga et al. (2022) where, using the *Gaia* DR3 astrometric data, plus astrometry from occultations (Gault et al. 2022), an upper limit of 1 g/cm^3 is determined, in agreement with the low density expected as Themis family member ((Marsset et al. 2016)), within the lower limit that we estimate from Eq. 10, $1.74 \pm 1.04 \text{ g/cm}^3$. This example stands out as a caveat about our use of average density estimates derived from spectral types, which cannot be taken at face value. Nonetheless, we can say that with our method we detected the companion satellites of Schober and Arecibo, with a low $\overline{SNR}$ (slightly below 1).

5.2. Comparison to the known population

Our candidate binaries can be compared to the existing population. As our observational biases are different from other techniques, the goal is not to reproduce the same distribution. In principle, we can discover asteroids with satellites whose dynamical properties are unusual, in particular in a domain of intermediate sizes (that we can conventionally define between 20 and 100 km) where traditional techniques have very limited capabilities of discovery. On the other hand, we can also reasonably expect that some of our candidates are similar, in physical and/or dynamical properties, to the binaries known so far.

A first comparison between the astrometric binary candidates and the known binary population is based on taxonomy. Our goal is to verify if an excess of S-type binaries is present in our sample, by an approach similar to Minker & Carry (2023). We start by grouping the taxonomic classes in large complexes, as shown in Table 4. Notably, P-type asteroids are in the C complex, not the X complex. The reference sample of asteroids was constructed based on a magnitude limit of absolute magnitude $H < 16$ and within ranges of $a \in [2, 3.5] \text{ au}$, $i \in [0^\circ, 30^\circ]$ and $e \in [0, 0.5]$ roughly matching the distribution of the sample of binary candidates.

The reference sample is selected by choosing 30 asteroids around each binary candidate, from a partition of the $4D(a, e, i, D)$ parameter space (see Minker & Carry (2023) for details).

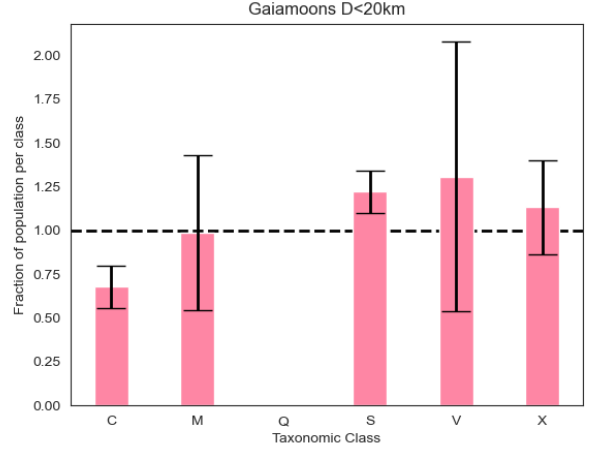


Fig. 17: Comparison of the fraction of small objects with $D < 20$ km in each taxonomic complex between the reference sample of background asteroids and our astrometric binary candidates' population. A taxonomic type with no column indicates that asteroids of that type are present in the reference population but not in the group of binary candidates.

Figure 17 shows the comparison between the reference sample and our binary candidates with $D < 20$ km, which represent most of our candidates. The S-complex taxonomic types present a fraction above 1, which means that there is an overrepresentation of objects of this complex in our sample of small binary candidates. On the other hand, our small candidates show a deficit of C-complex taxonomic types in comparison with the background asteroid population.

The results from this analysis are in great agreement with Minker & Carry (2023), where it is shown that even though chondritic asteroids are the most common type in the Solar System, there is a preferential presence of S-type over C-type, among binary objects at small diameters. Thus, we can conclude that the taxonomic distribution of our candidates is comparable to the one of the previously known population.

Taking a closer look at the sub-sample with $30 < D < 50$ km, we find no dominance of any taxonomic type (Fig. 18), suggesting a disconnect between the small- and medium-sized binary asteroid populations. However, statistical comparisons to a known population are not possible, as the only known binary asteroid in this size range is the system (243) Ida – Dactyl. Interestingly, it was discovered by a spacecraft during a fly-by (Chapman et al. 1995). This could indicate that un-conventional techniques such as the astrometric method are necessary to find similar binaries. The limited presence of large ($D > 50$ km) asteroids in our sample of binary candidates eliminates the possibility of continuing this taxonomic analysis at larger sizes.

In order to compare the dynamical properties of our candidates to the known population, we first present (Fig. 19) the distribution of the primary rotation period as a function of the estimated primary diameter. The rectangles in the plot represent a raw approximation of the known binary asteroid groups (Pravec & Harris 2007, Pravec et al. 2010, Margot et al. 2015). Group L is for fast-rotating and large objects. Group A represents small primary asteroids with fast rotation; B, systems with small primaries but size ratios $D_2/D_1 \sim 1$ that rotate slower as the primary diameter increases.

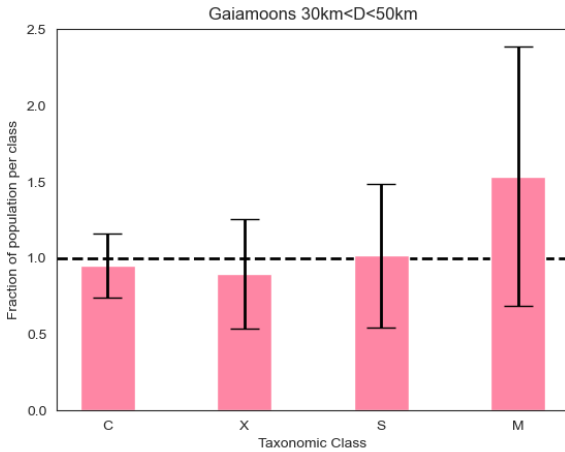
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	Number of candidates
Asteroids in DR3	156,801
Candidates with a reasonably long sequence of observations	30,030
Candidates' time series with detection from the statistical selection	3,038
Candidates' time series with physically meaningful density estimate	934
Candidates with separation beyond the Roche limit	358
Candidates from the taxonomic filtering	156
Best candidates with $\hat{S}\hat{N}\hat{R} > 1$	67

Table 3: Number of binary candidates remaining after each stage of the systematic search.

Table 4: Taxonomic classes grouped as complexes (Σ).

Classes	Σ
S	S
Q	Q
V	V
C, Ch, B, D, P, Z	C
X	X, E
K, L, M	M

Fig. 18: Fraction of binary candidates with $30 < D < 50$ km in each taxonomic complex, with respect to the reference sample of background asteroids.

The first striking feature of our sample is the partial overlap with the pre-existing population discovered by photometry (Group A), which clearly appears below ~ 20 km. Some candidates also partially overlap group B, but their mass ratios are small in general (order of 0.1).

At the other extreme of the size range, binary candidates from our search do not match group L (besides one). This is expected, as the wobbling signal from large objects should not be dominated by a small satellite, but by the photocentre displacements on the shape of the primary alone. Coherently with this interpretation, some potential candidates in this region are excluded due to the separation being too small relative to the Roche radius.

Eventually, intermediate sizes (20-100 km), clearly under-represented in the known sample, are present for our astrometric candidates, directly confirming the new potential of this technique.

The comparison of satellite orbits and sizes is more difficult and intrinsically ambiguous, as our analysis introduces two fam-

ilies of solutions, corresponding to two different possible ranges of mass ratio, as shown in Fig. 13.

The estimated mass ratio intervals for the **67** selected best binary candidates, and their respective primary rotation periods, are shown in Fig. 20. The two mass ratio intervals are more or less separated depending on the minimum estimated density for the system. At this stage, we have no criteria to favour a solution over the other. However, we notice that objects of intermediate size populate preferentially extreme values of the mass ratio. This could imply that binaries of similar-sized components could exist in that population.

The analysis of the ratio between the wobble (orbital) period and primary rotation period, reveals the presence of synchronous objects and, to a minor extent, of objects in a 1:2 period ratio (Fig. 21). Among the known Main Belt binaries, almost all those with $D_s/D_p > 0.5$ are synchronous, as the tidal coupling is more efficient for large satellites. Applied to our sample, this evidence would imply that large mass ratios have a higher probability to show orbit/spin coupling. (4337) Arecibo, at $D_s/D_p > 0.53$ and synchronous, clearly falls in this category. Periods on the 1:2 ratio could simply represent an alias and could be considered synchronous too. Interestingly, intermediate-size objects are in large majority in this category.

6. Discussion

As explained above, this first attempt of binary search in *Gaia* DR3 astrometry is performed by adopting some conservative criteria and an approach that does not take into account all the observations available for each asteroid. Other choices are possible, such as those described in Segev et al. (2023), where a solution of the complete inverse problem leading to satellite orbits, and involving all the AL residuals of each object, is proposed. Their search is not successful and the main explanation given is the rejection mechanism of astrometric outliers implemented by the validation pipeline in DR2 (Gaia Collaboration et al. 2018).

However, our results show that periodic fluctuations in the residuals are compatible with the expected amplitude and orbital periods of satellites. We thus think that the missed detection in the cited article is due to three main reasons: the strong increase in the time range and number of asteroids of *Gaia* DR3 concerning DR2 (by factors 1.5 and 11, respectively); the improved astrometric quality of DR3; and, of lesser importance, the possible presence of systematic errors in isolated astrometric measurements that are included in the analysis.

Concerning the first argument, by simple statistical scaling we can estimate that, if DR2 astrometry were good enough to reveal our best candidates, only a few of them (< 10) would have been found. However, the probability of detection is not a linear function of the time range, as a reduction in the observed arc can have a strong adverse impact on the quality of the orbital fit and, in turn, on its residuals.

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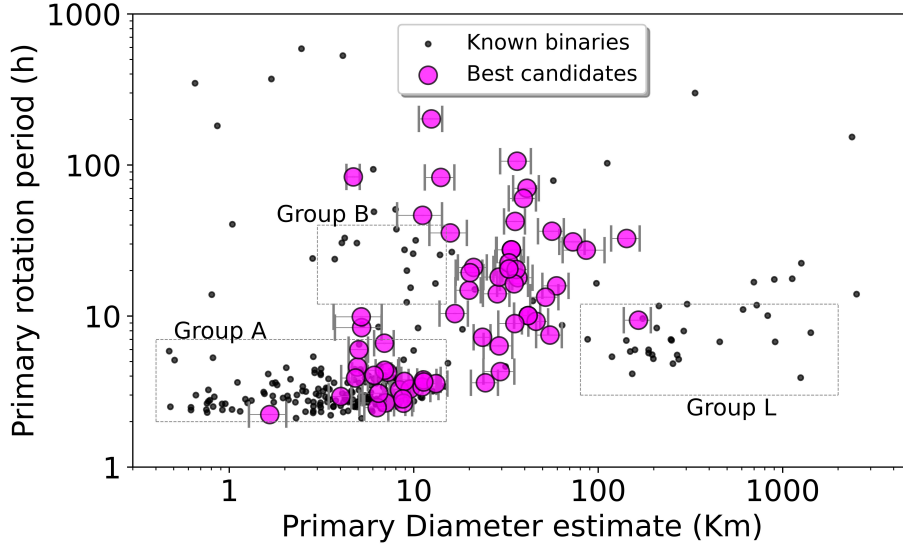


Fig. 19: Plot of the primary rotation period versus the estimated primary diameter for the best candidates. The black dots are known binaries in the shown intervals and the magenta circles are the best binary candidates we obtain.

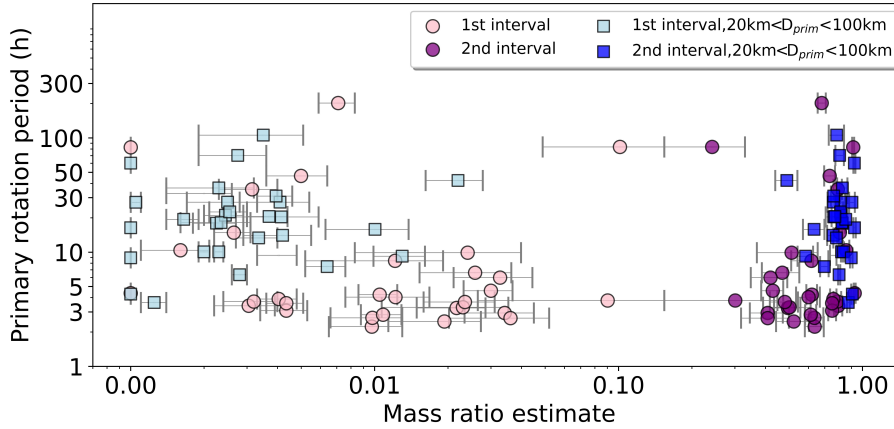


Fig. 20: Plot of the primary rotation period versus the estimated mass ratio intervals for the 67 selected candidates. The light-coloured and darker-coloured circles represent, respectively, the first and second intervals of possible mass ratio values for the best binary candidates.

The fact that DR3 improves astrometric quality in a significant way over DR2, is well visible not only in the overall statistics but also in specific cases such as (4337) Arecibo, whose residuals show a clear trend in DR3 (Tanga et al. 2022) but less clearly in DR2 (Fig. 19 in Segev et al. 2023), over the same time span.

Hence, this is the first work that provides a large list of binary candidates obtained from astrometry and crosses dedicated statistical and physical selection criteria. At this stage, without independent confirmation of the binary status and a clear discrimination between the two solutions that we obtain for each candidate, the impact of our possible discoveries on formation scenarios cannot be very specific. However, some general considerations can be attempted.

First, the intermediate size range (20-100 km) where very few binaries are currently known (only ~5% of the total population) is probably the most interesting, and the one having a

stronger potential impact. If they are synchronous and have large mass ratios, a well-known prototype at large sizes can be considered the asteroid (90) Antiope (size ratio ~0.95, diameter ~88 km (Merline et al. 2000)). Even though there are several theories for the formation of the Antiope system (Pravec & Harris 2007, Weidenschilling et al. 2001), observations support the hypothesis that the Antiope system objects were formed simultaneously from the disruption of a parent body (Descamps et al. 2009, Marchis et al. 2011).

With a similar mechanism, as shown in numerical simulations (Doressoundiram et al. 1997, Durda et al. 2004), Escaping Ejecta Binaries (EEBs) result from the creation of collisional fragments at low relative velocity, that remain gravitationally bound. They preferentially have highly eccentric orbits, that could be circularised by tidal forces in their secular evolution. They should not have particularly fast primary rotation as they are not created by fission or fragment ejection. However, the cur-

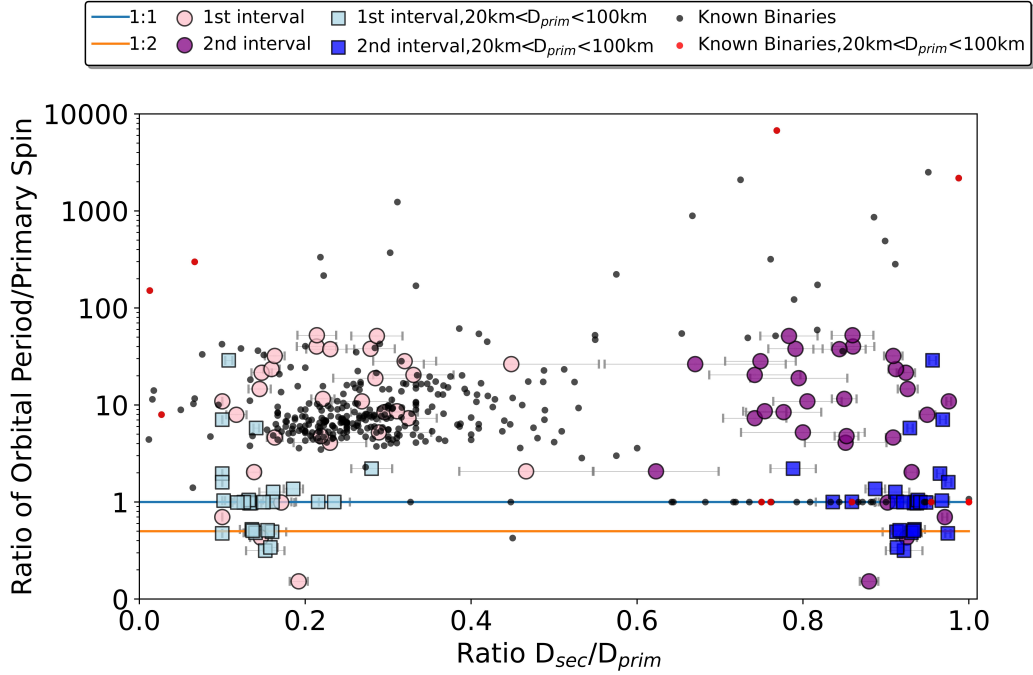
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Fig. 21: Plot of the ratio of the estimated orbital period (or wobble period) of the secondary over the photometric rotation period of the primary versus the estimated size ratio of the binary system. The black dots represent all of the known binaries and the red dots highlight those with intermediate sizes ($20 \text{ km} < D_{\text{primary}} < 100 \text{ km}$). Meanwhile, the light and dark purple disks represent the average value of the best-estimated size ratio intervals for objects smaller than 20 km and the light and dark blue disks represent the larger objects. The blue line shows the condition where the estimated orbital period of the secondary is almost equal to the rotation period of the primary object, representing a 1:1 period ratio, while the orange line represents the 1:2 period ratio.

rent sample of known binaries, if simulations are correct, has a clear under-representation of this category. The only good candidate is (317) Roxane with its satellite Olympias (Drummond et al. 2021). The population of EEBs could also be compatible with binary Mars impactors revealed by (Vavilov et al. 2022). Once validated, our sample could clearly contribute to revealing many details about the presence, origin and evolution of EEBs.

We also notice the compatibility of our highest mass ratio solutions with the findings by Scheeres (2007) and (Pravec et al. 2010), that determine (theoretically and by observations) the conditions for splitting of pairs created by fission. Their main finding is a general tendency to create separate pairs when the mass ratio is < 0.2 , which is about the inferior threshold for our distribution of high mass ratio solutions when small asteroids $< 20 \text{ km}$ are considered (magenta circles in Fig. 20). Some of the systems close to (and above) that critical splitting threshold, could have been produced by fission. Considering that mass shedding and re-accumulation in orbit is the most likely formation process for small asteroids ($D \lesssim 20 \text{ km}$) (Pravec & Harris 2007, Walsh et al. 2008), we expect that future observations characterising our sample should find results compatible with the known population in this size range.

7. Conclusions

Our work presents a simple but robust method to detect periodic signals in the residuals of the orbital fit in *Gaia* astrometry, which is compatible with the presence of binary asteroids. We explore all astrometric data of asteroids available in the DR3 catalogue

and, after a careful selection process combining statistical and physical analyses, we obtain a consolidated list of candidates that are likely to be binary asteroids.

Among the strengths of our results, we can stress the presence fraction of our candidates has similar physical properties as the known binary population (small asteroids with companions discovered by photometry) but also spans over a parameter range that tends to fill the gap where other techniques have been failing to find binaries, as expected from preliminary studies (Mignard et al. 2007, Pravec & Scheirich 2012). The distribution of the taxonomy of our candidate binaries also provides interesting matches to the known population and some potentially new evidence. We notice also a large fraction of possible synchronous binaries, that are notoriously difficult to discover by photometry, especially if the secondary rotation is also synchronised (doubly synchronous binaries).

Some limitations of our approach are also clear. As we deal with an astrometric accuracy of the order of 1 mas, we cannot exclude that some signals are not due to companions, but to the photocentre displacement occurring during the rotation of irregular, single asteroids. This could be the case, especially for the largest objects approaching the 100 km diameter, although the relatively small phase angles should mitigate the effect. We also notice that our comparison with known satellites is limited to a very small sample, but seems to point out that in some cases we detect companions, although not with the parameters derived by previous surveys.

Future improvements may involve many aspects: the exploitation of the astrometry could adopt a more refined error model at the transit level; the inclusion of observations more distant in time, with an increase of the accessible period range; a more complex model for the astrometric signal, involving flattening of the components and non-uniform illumination; a more detailed analysis of the spectral properties and the choices of sizes, plausible density; etc.

Other *Gaia* data releases, such as the Focused Product Release (which appeared in October 2023) and, in particular, the DR4 (including all the asteroid astrometry from the nominal mission) certainly will offer opportunities to consolidate our approach and refine the results. We expect the astrometric quality to increase further, and the number of consecutive data sequences (also for the same asteroid) to be more frequent.

Despite these limitations, we think that we have disclosed the capabilities of *Gaia* in discovering asteroid satellites by the astrometric method, and we have set the foundations for future, more refined searches. **Stellar occultation campaigns focused on our candidates may pin down the orbits, size and shape of the companions. In the absence of our *Gaia* binary candidates, the stellar occultation observations to search for asteroid companions are unlikely to succeed, and without the stellar occultation technique, it is hard to assess some of the estimated sizes of the companions. Additionally, for the other candidates with similar characteristics to the known binary population, the photometric light curve could be sufficient to determine the presence of a companion in some cases. Therefore,** we warmly invite the community to collaborate on the campaigns that we are organising, by photometry and stellar occultations, to validate our findings and physically characterise the confirmed binaries.

8. Acknowledgements

This work presents results from the European Space Agency (ESA) space mission *Gaia*. *Gaia* data are being processed by the *Gaia* Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular, the institutions participating in the *Gaia* Multilateral Agreement (MLA). The *Gaia* mission website is <https://www.cosmos.esa.int/Gaia>. The *Gaia* archive website is <https://archives.esac.esa.int/Gaia>.

This work was supported by the project *Gaia* Moons of the Agence Nationale de Recherche (France), grant ANR-22-CE49-0002.

It was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, also by CAPES-PRINT Process 88887.570251/2020-00, by the French Programme National de Planetologie, and by the BQR program of Observatoire de la Côte d’Azur.

We made use of the software products: SsODNet VO service of IMCCE, Observatoire de Paris (Berthier et al. 2022); Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013, 2018, 2022); Matplotlib (Hunter 2007); Multiprocess package (McKerns & Aivazis 2010, McKerns et al. 2012).

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Appendix A: Amplitude offset

To evaluate the statistical significance of the highest GLSP peak, we explained in Sec. 4.1 that we use Monte Carlo simulations. Their purpose is to generate a large number of synthetic times series that are consistent with our model when there is no sinusoid, i.e., an unknown constant sampled at the same time sampling grid as the data set under investigation plus noise consistent with the data error bars.

Therefore, to generate unknown constants (offsets) that are consistent with our *Gaia* residual time series, we estimated this offset from a large number of time series and plotted its distribution. The result is in Fig. A.1, limited between -2 and 2 mas for visualisation purposes.

The Figure compares the empirical distribution with a Laplacian (magenta, parameters μ and b) and Gaussian (red, parameters μ and σ) best fit. Clearly, the Laplacian fit is better and we use this distribution to generate offsets in the Monte Carlo simulations.

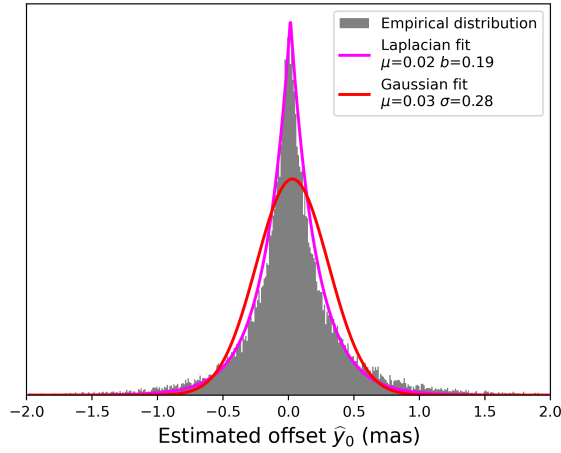


Fig. A.1: Histogram of distribution of the estimated offset $\hat{y}_0$ for each window of search explored. The grey bars represent the empirical distribution, while the coloured lines represent different distributions fitted to the data and their respective best-fit parameters.

Appendix B: Asteroid binary candidates list

Table B.1: List of estimated parameters for the *Gaia* astrometric asteroid binary candidates. The grey lines represent the objects with density constrained by taxonomy, and the magenta lines indicate the best candidates accounting for the taxonomic correction and a strong detection with $\widehat{SNR} > 1$.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{SNR} > 1$
KNOWN BINARIES								
317	127.56±64.57	2.38±1.69	(5.08±4.79)e+02	(1.21±1.11)e-02	(5.27±5.27)e+04	(7.36±2.63)e-01		*
1509	123.71±11.09	5.09±0.54	(7.24±1.10)e+01	(2.17±0.68)e-02	(6.70±0.98)e+01	(4.95±0.61)e-01	*	*
2871	20.69±4.63	0.45±0.07	(1.56±0.18)e+01	(1.18±0.25)e-02	(1.43±0.16)e+01	(6.00±0.38)e-01	*	
4337	35.93±6.36	0.61±0.07	(6.57±0.66)e+01	(2.40±0.40)e-03	(5.99±0.62)e+01	(8.18±0.17)e-01	*	
5817	152.72±80.10	1.61±1.19	(6.27±1.29)e+01	(1.22±0.46)e-02	(5.72±1.14)e+01	(6.01±0.67)e-01	*	*
OBJECTS WITH TWO SOLUTIONS								
	10.02±0.02	0.74±0						
542	10.04±0.04	0.56±0.01	(7.64±0.20)e+01	(2.30±0.10)e-03	(6.90±0.19)e+01	(8.20±0.05)e-01	*	*
	14.37±0.19	0.48±0.01						
2219	13.56±0.36	0.74±0.06	(5.59±1.10)e+01	(2.50±0.80)e-03	(5.08±0.99)e+01	(8.16±0.33)e-01	*	*
	63.47±13.54	0.68±0.05						
9573	57.59±3.56	0.99±0.05	(3.37±0.57)e+01	(1.08±0.33)e-02	(3.08±0.50)e+01	(6.18±0.53)e-01	*	
	10.33±0.13	0.56±0.05						
10766	73.57±9.51	0.87±0.55	(1.17±0.24)e+02	(4.99±1.70)e-03	(1.07±0.22)e+02	(7.36±0.48)e-01	*	
OBJECTS WITH ONE SOLUTION								
53	9.08±0.01	1.42±0.01	(2.39±0.96)e+02	(2.50±1.50)e-03	(2.54±1.25)e+02	(8.34±0.76)e-01		*
203	23.89±0.27	0.88±0.01	(2.32±0.03)e+02	(1.00±0)e-03	(5.94±3.71)e+02	(9.35±0.39)e-01		*
217	12.70±0.04	0.88±0.02	(1.84±0.82)e+02	(2.75±1.75)e-03	(2.19±1.25)e+02	(8.33±0.88)e-01		*
238	9.85±0.01	2.23±0.02	(3.23±1.07)e+02	(2.00±1.00)e-03	(3.92±1.96)e+02	(8.59±0.66)e-01		*
247	12.10±0.06	0.55±0.02	(1.46±0.05)e+02	(1.00±0)e-03	(4.41±2.38)e+02	(9.53±0.24)e-01		*
264	9.25±0.01	1.04±0.01	(7.11±0.89)e+01	(1.30±0.31)e-02	(6.52±0.80)e+01	(5.84±0.43)e-01	*	*
280	33.92±0.16	1.58±0.01	(1.35±0.25)e+02	(2.75±0.85)e-03	(1.23±0.23)e+02	(8.06±0.33)e-01	*	*
370	11.39±0.22	0.47±0.06	(6.51±0.69)e+01	(2.55±0.45)e-03	(5.98±0.66)e+01	(8.13±0.19)e-01	*	*
448	12.27±0.07	0.86±0.03	(1.13±0.37)e+02	(1.85±0.85)e-03	(1.53±0.84)e+02	(8.70±0.64)e-01		*
449	38.35±0.40	1.08±0.01	(1.83±0.45)e+02	(2.30±0.90)e-03	(1.68±0.42)e+02	(8.27±0.40)e-01	*	*
476	28.22±0.16	1.08±0.02	(1.75±0.05)e+02	(1.05±0.05)e-03	(2.08±0.56)e+02	(9.05±0.24)e-01	*	*
477	19.19±0.10	0.57±0.01	(5.11±0.47)e+01	(1.65±0.25)e-03	(4.68±0.44)e+01	(8.53±0.13)e-01	*	*
487	13.28±0.15	0.74±0.03	(1.04±0.12)e+02	(3.35±0.65)e-03	(9.37±1.05)e+01	(7.81±0.22)e-01	*	*
488	16.37±0.05	1.06±0.01	(2.52±0.47)e+02	(2.00±0.60)e-03	(2.35±0.46)e+02	(8.40±0.29)e-01	*	*
504	11.33±0.05	0.71±0.03	(1.00±0.54)e+02	(7.44±5.64)e-03	(9.21±5.01)e+01	(7.12±1.33)e-01		*
516	10.23±0.02	1.23±0.01	(9.09±0.97)e+01	(6.39±1.20)e-03	(8.31±0.88)e+01	(6.98±0.28)e-01	*	*
519	18.00±0.28	0.60±0.01	(8.90±1.08)e+01	(2.25±0.45)e-03	(8.16±1.09)e+01	(8.25±0.22)e-01	*	*
521	27.45±0.26	2.01±0.04	(2.34±0.05)e+02	(1.00±0)e-03	(6.25±3.27)e+02	(9.47±0.26)e-01		*
532	9.48±0.06	2.07±0.03	(2.64±0.29)e+02	(4.04±0.75)e-03	(2.39±0.26)e+02	(7.58±0.23)e-01	*	*
550	10.51±0.03	1.19±0.04	(5.58±0.62)e+01	(3.70±0.70)e-03	(5.08±0.59)e+01	(7.70±0.24)e-01	*	*
552	8.54±0.03	0.66±0.01	(1.52±0.44)e+02	(1.75±0.75)e-03	(2.00±1.02)e+02	(8.73±0.61)e-01		*
556	30.29±0.25	0.69±0	(8.22±0)e+01	(1.00±0)e-03	(9.29±1.08)e+01	(9.08±0.10)e-01	*	*
562	36.80±0.99	0.73±0.02	(1.25±0.05)e+02	(2.80±0.20)e-03	(1.14±0.05)e+02	(8.02±0.08)e-01	*	*
605	15.89±0.14	1.46±0.02	(1.17±0.24)e+02	(1.00±0.37)e-02	(1.07±0.22)e+02	(6.34±0.64)e-01	*	*
616	16.41±0.45	0.29±0.02	(4.53±0.62)e+01	(2.45±0.55)e-03	(4.12±0.59)e+01	(8.16±0.24)e-01	*	
625	20.46±0.26	0.45±0	(5.65±0.63)e+01	(2.45±0.45)e-03	(5.10±0.57)e+01	(8.15±0.19)e-01	*	*
674	10.56±0.07	0.84±0.02	(1.24±0.12)e+02	(3.94±0.65)e-03	(1.13±0.11)e+02	(7.62±0.21)e-01	*	*
699	49.70±0.91	1.10±0.04	(5.36±0.90)e+01	(3.05±0.85)e-03	(4.88±0.81)e+01	(7.94±0.31)e-01	*	*
712	9.67±0.02	0.69±0.01	(1.81±0.17)e+02	(1.15±0.15)e-03	(3.09±1.61)e+02	(9.13±0.43)e-01		*

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
720	17.49±0.13	0.45±0.01	(7.58±0)e+01	(1.00±0)e-03	(7.70±0.85)e+01	(8.99±0.11)e-01	*	*
723	27.16±8.38	0.42±0.04	(9.38±3.55)e+01	(1.85±0.85)e-03	(1.88±1.35)e+02	(8.81±0.77)e-01		*
810	47.92±1.91	0.23±0	(2.03±0)e+01	(1.00±0)e-03	(2.98±0.36)e+01	(9.29±0.08)e-01	*	*
838	11.83±0.09	0.64±0.05	(1.41±0.53)e+02	(1.90±0.90)e-03	(2.00±1.19)e+02	(8.70±0.67)e-01		*
858	30.23±0.74	0.51±0.01	(7.29±0.74)e+01	(2.65±0.45)e-03	(6.60±0.71)e+01	(8.07±0.19)e-01	*	*
879	58.16±2.90	0.51±0.09	(5.60±0)e+01	(1.00±0)e-03	(6.83±0.73)e+01	(9.15±0.09)e-01	*	*
923	15.02±0.35	0.42±0.02	(6.86±1.54)e+01	(1.40±0.40)e-03	(1.14±0.65)e+02	(8.97±0.54)e-01		*
930	94.11±23.34	0.38±0.03	(1.02±0)e+02	(1.00±0)e-03	(1.73±0.44)e+02	(9.35±0.16)e-01	*	
950	30.80±1.14	0.57±0.07	(4.33±0.41)e+01	(7.09±1.20)e-03	(3.93±0.37)e+01	(6.81±0.26)e-01	*	*
1024	33.45±0.50	0.81±0.03	(1.10±0.31)e+02	(3.49±1.60)e-03	(9.97±2.85)e+01	(7.83±0.56)e-01	*	*
1032	82.12±14.23	0.38±0.02	(1.28±0.07)e+02	(1.00±0)e-03	(7.11±4.37)e+02	(9.71±0.17)e-01		
1109	32.07±0.14	1.48±0.04	(2.28±0.39)e+02	(1.30±0.30)e-03	(3.63±1.90)e+02	(9.02±0.47)e-01		*
1127	12.77±0.11	0.72±0.03	(1.14±0.39)e+02	(1.90±0.90)e-03	(1.50±0.82)e+02	(8.67±0.66)e-01		*
1194	20.45±0.31	1.10±0.01	(7.79±2.00)e+01	(4.14±1.75)e-03	(7.07±1.82)e+01	(7.62±0.55)e-01	*	*
1200	8.96±0.06	0.62±0.01	(7.68±2.59)e+01	(2.00±1.00)e-03	(9.80±5.14)e+01	(8.62±0.67)e-01		*
1237	26.15±0.95	0.41±0.01	(6.38±0)e+01	(1.00±0)e-03	(9.23±1.34)e+01	(9.27±0.10)e-01	*	*
1359	28.68±9.70	0.38±0.13	(7.83±0)e+01	(1.00±0)e-03	(1.10±0.14)e+02	(9.26±0.09)e-01	*	*
1408	14.63±0.31	0.53±0.03	(5.12±0.94)e+01	(8.59±2.79)e-03	(4.67±0.85)e+01	(6.56±0.54)e-01	*	
1438	20.48±0.71	0.42±0.04	(5.98±1.19)e+01	(4.04±1.35)e-03	(5.45±1.10)e+01	(7.63±0.43)e-01	*	
1457	15.32±1.84	0.38±0.03	(3.46±0.56)e+01	(3.15±0.85)e-03	(3.17±0.53)e+01	(7.91±0.32)e-01	*	*
1464	28.69±1.35	0.36±0.12	(6.09±1.25)e+01	(2.70±0.90)e-03	(5.59±1.18)e+01	(8.09±0.37)e-01	*	
1481	85.80±7.18	0.57±0.03	(1.07±0.06)e+02	(1.00±0)e-03	(4.07±2.35)e+02	(9.60±0.21)e-01		*
1569	24.60±0.70	0.93±0.02	(8.55±1.62)e+01	(6.84±2.25)e-03	(7.79±1.46)e+01	(6.91±0.51)e-01	*	*
1602	6.56±0.44	0.64±0.12	(2.75±1.53)e+01	(8.28±7.10)e-02	(2.57±1.35)e+01	(3.75±2.22)e-01		
1639	11.23±0.09	0.61±0.06	(8.30±3.32)e+01	(1.95±0.95)e-03	(1.22±0.77)e+02	(8.68±0.71)e-01		*
1764	104.69±27.22	1.17±0.41	(1.92±0.14)e+02	(1.25±0.15)e-03	(1.76±0.17)e+02	(8.74±0.11)e-01	*	*
1800	27.05±0.20	0.80±0.02	(1.57±0.33)e+01	(1.93±0.79)e-02	(1.45±0.29)e+01	(5.22±0.80)e-01	*	*
1829	20.36±0.69	0.64±0.01	(1.89±0.18)e+01	(1.05±0.19)e-02	(1.73±0.17)e+01	(6.19±0.31)e-01	*	*
1867	52.49±1.97	0.77±0.02	(2.87±0.07)e+02	(1.00±0)e-03	(9.74±5.19)e+02	(9.58±0.21)e-01		*
1879	46.94±3.39	0.70±0.05	(2.97±0.39)e+01	(1.81±0.48)e-02	(2.74±0.35)e+01	(5.25±0.50)e-01	*	
1901	50.58±8.24	0.57±0.22	(9.49±2.43)e+01	(3.60±1.50)e-03	(8.69±2.30)e+01	(7.79±0.53)e-01	*	
1963	17.67±0.24	0.57±0.03	(5.46±1.07)e+01	(2.35±0.75)e-03	(5.02±0.99)e+01	(8.23±0.32)e-01	*	*
1967	32.78±1.01	0.93±0.02	(3.14±0.32)e+01	(1.08±0.20)e-02	(2.87±0.28)e+01	(6.13±0.32)e-01	*	*
2032	56.28±3.73	0.65±0.01	(1.36±0)e+02	(1.00±0)e-03	(1.48±0.13)e+02	(9.06±0.08)e-01	*	*
2105	52.01±0.88	0.82±0.02	(8.32±0.20)e+01	(1.00±0)e-03	(1.63±0.85)e+02	(9.29±0.35)e-01		*
2611	99.95±47.36	2.11±1.51	(8.47±1.98)e+01	(9.01±6.37)e-02	(8.11±1.61)e+01	(3.01±1.47)e-01	*	*
2668	5.36±0.03	0.56±0.04	(1.10±0.38)e+01	(8.72±6.66)e-02	(1.04±0.33)e+01	(3.24±1.70)e-01		
2713	16.58±0.30	0.42±0.01	(3.04±0.31)e+01	(4.34±0.75)e-03	(2.76±0.27)e+01	(7.50±0.22)e-01	*	*
2786	24.70±0.49	0.88±0.06	(2.74±0.16)e+01	(1.12±0.42)e-01	(2.69±0.11)e+01	(2.09±0.55)e-01	*	
3099	97.98±49.25	4.08±1.80	(9.32±8.63)e+02	(7.74±7.64)e-02	(9.59±9.58)e+04	(5.76±4.23)e-01		*
3206	173.09±77.04	2.32±1.80	(4.88±0.56)e+01	(1.01±0.52)e-01	(4.74±0.42)e+01	(2.42±0.88)e-01	*	*
3211	36.48±0.52	0.85±0.01	(5.99±3.08)e+01	(5.39±3.99)e-03	(5.56±2.90)e+01	(7.52±1.16)e-01		*
3220	26.30±9.25	0.94±0.20	(1.46±1.28)e+02	(7.74±7.64)e-02	(1.46±1.46)e+04	(5.76±4.23)e-01		
3382	16.98±0.49	0.35±0.02	(1.25±0.14)e+01	(1.05±0.21)e-02	(1.15±0.13)e+01	(6.19±0.35)e-01	*	
3457	45.95±2.75	0.81±0.02	(5.74±0.94)e+01	(4.99±1.40)e-03	(5.20±0.82)e+01	(7.33±0.37)e-01	*	*
3541	58.70±6.72	0.97±0.32	(5.95±0.81)e+01	(1.43±0.37)e-02	(5.45±0.71)e+01	(5.67±0.47)e-01	*	
3561	59.22±10.15	0.45±0.02	(9.77±0.43)e+01	(1.00±0)e-03	(3.05±1.86)e+02	(9.49±0.29)e-01		*
3596	13.63±0.52	0.76±0.06	(2.72±1.41)e+02	(3.10±2.10)e-03	(2.98±1.78)e+02	(8.18±0.93)e-01		*
3631	15.58±0.27	0.77±0.03	(6.45±1.23)e+01	(9.23±3.14)e-03	(5.88±1.10)e+01	(6.45±0.57)e-01	*	*
3728	26.10±7.36	0.58±0.16	(5.12±0.94)e+01	(8.29±2.69)e-03	(4.68±0.86)e+01	(6.62±0.53)e-01	*	

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
3731	16.33±0.22	0.89±0.02	(1.59±0.50)e+02	(1.85±0.85)e-03	(2.06±1.07)e+02	(8.68±0.63)e-01		*
3800	89.49±14.27	0.94±0.17	(1.18±0.22)e+01	(9.73±3.24)e-03	(1.08±0.20)e+01	(6.37±0.57)e-01	*	*
3819	79.60±2.78	0.92±0.55	(6.45±0.97)e+01	(3.20±0.80)e-03	(5.88±0.87)e+01	(7.89±0.28)e-01	*	*
3864	49.17±6.70	0.26±0.03	(2.55±1.01)e+01	(1.85±0.85)e-03	(5.98±4.59)e+01	(8.85±0.80)e-01		
3979	105.55±53.61	3.73±1.83	(8.49±7.93)e+02	(7.74±7.64)e-02	(8.77±8.76)e+04	(5.76±4.23)e-01		*
4031	6.66±0.02	0.82±0.04	(9.75±4.12)e+00	(8.36±7.02)e-02	(9.17±3.54)e+00	(3.64±2.10)e-01		*
4332	62.38±6.44	1.41±0.04	(5.59±1.55)e+01	(2.30±1.23)e-02	(5.15±1.36)e+01	(5.02±1.11)e-01	*	*
4482	13.30±0.24	0.73±0.06	(2.79±1.52)e+01	(8.10±7.28)e-02	(2.60±1.33)e+01	(4.05±2.51)e-01		
4875	38.18±2.66	0.74±0.05	(1.85±0.21)e+01	(5.76±1.95)e-02	(1.76±0.18)e+01	(3.11±0.66)e-01	*	
4950	15.60±0.51	0.74±0.11	(3.91±2.47)e+01	(8.02±7.36)e-02	(3.62±2.17)e+01	(4.22±2.68)e-01		
4999	42.60±8.93	0.35±0.13	(5.93±3.26)e+01	(1.55±0.55)e-03	(4.92±4.90)e+03	(9.16±0.83)e-01		
5044	34.75±1.74	0.52±0.04	(1.78±0.44)e+01	(4.23±2.38)e-02	(1.66±0.38)e+01	(3.94±1.22)e-01	*	
5157	43.35±19.11	1.04±0.32	(2.53±2.25)e+02	(3.63±3.53)e-02	(2.55±2.55)e+04	(6.29±3.70)e-01		
5208	14.88±0.40	0.60±0.04	(1.74±0.17)e+01	(1.04±0.50)e-01	(1.69±0.12)e+01	(2.31±0.77)e-01	*	
5292	62.31±15.59	0.18±0.06	(3.16±0)e+01	(1.00±0)e-03	(4.36±0.77)e+01	(9.23±0.13)e-01	*	
5329	11.77±0.10	0.69±0.03	(3.72±2.05)e+01	(4.84±3.64)e-03	(3.36±1.84)e+01	(7.64±1.12)e-01		*
5390	32.26±0.88	0.52±0.01	(2.25±1.21)e+01	(8.98±6.99)e-03	(2.04±1.09)e+01	(6.88±1.45)e-01		*
5507	22.75±0.59	0.43±0.10	(3.71±2.82)e+01	(7.24±6.24)e-03	(3.92±3.09)e+01	(7.39±1.66)e-01		
5747	11.69±0.15	0.81±0.04	(3.15±1.63)e+01	(8.11±7.27)e-02	(2.93±1.41)e+01	(4.02±2.48)e-01		*
5917	54.19±4.04	1.91±0.11	(3.41±0.66)e+01	(3.60±1.59)e-02	(3.19±0.57)e+01	(4.08±0.91)e-01	*	*
5995	24.57±2.20	0.26±0.10	(2.00±0.19)e+01	(2.25±0.35)e-03	(1.84±0.19)e+01	(8.25±0.17)e-01	*	
6093	51.80±3.94	0.79±0.03	(2.15±0.77)e+01	(2.41±1.58)e-02	(1.97±0.68)e+01	(5.12±1.43)e-01	*	*
6129	35.80±2.81	0.96±0.07	(4.61±1.23)e+01	(2.28±1.18)e-02	(4.25±1.08)e+01	(5.02±1.06)e-01	*	
6261	27.27±1.93	1.04±0.15	(3.44±1.88)e+01	(8.21±7.17)e-02	(3.22±1.65)e+01	(3.86±2.32)e-01		
6359	17.85±0.23	0.57±0.01	(5.40±0.99)e+01	(4.19±1.30)e-03	(4.92±0.94)e+01	(7.57±0.41)e-01	*	*
6364	55.96±2.47	1.33±0.02	(4.72±0.69)e+01	(2.08±0.62)e-02	(4.35±0.61)e+01	(5.01±0.58)e-01	*	*
6425	63.51±6.00	0.21±0.02	(2.19±0)e+01	(1.00±0)e-03	(5.32±0.18)e+01	(9.57±0.01)e-01	*	
6612	25.83±1.44	0.71±0.19	(4.83±3.67)e+01	(7.90±7.48)e-02	(4.46±3.30)e+01	(4.54±3.00)e-01		
6702	18.92±0.67	1.08±0.18	(6.26±4.06)e+01	(8.00±7.38)e-02	(5.80±3.60)e+01	(4.26±2.72)e-01		
6851	5.39±0.05	0.55±0.04	(8.38±3.84)e+00	(8.31±7.07)e-02	(7.88±3.34)e+00	(3.71±2.17)e-01		
6950	99.11±27.86	0.92±0.21	(4.91±0.63)e+01	(4.34±0.95)e-03	(4.46±0.56)e+01	(7.50±0.28)e-01	*	*
7065	94.86±1.81	8.05±0.71	(2.40±1.26)e+02	(8.15±7.23)e-02	(2.23±1.10)e+02	(3.95±2.41)e-01		*
7071	27.29±4.41	0.81±0.27	(4.47±1.01)e+01	(1.13±0.46)e-02	(4.10±0.92)e+01	(6.16±0.73)e-01	*	
7083	17.91±0.44	0.40±0.01	(2.22±0.47)e+01	(4.34±1.55)e-03	(2.01±0.42)e+01	(7.53±0.46)e-01	*	*
7093	78.78±13.16	0.39±0.02	(2.70±0.56)e+01	(1.65±0.55)e-03	(2.48±0.52)e+01	(8.56±0.28)e-01	*	
7143	189.00±108.91	2.46±1.76	(1.30±0.20)e+02	(2.35±0.76)e-02	(1.20±0.18)e+02	(4.80±0.63)e-01	*	*
7534	92.84±33.46	1.14±0.14	(3.20±0.39)e+01	(3.39±0.98)e-02	(2.99±0.34)e+01	(4.08±0.57)e-01	*	
7642	69.70±26.87	1.06±0.71	(1.89±1.81)e+02	(7.74±7.64)e-02	(1.98±1.98)e+04	(5.76±4.23)e-01		
7881	34.25±3.82	1.08±0.49	(2.60±2.41)e+02	(7.74±7.64)e-02	(2.67±2.67)e+04	(5.76±4.23)e-01		
8284	81.51±1.79	7.07±0.82	(2.67±1.70)e+02	(7.97±7.41)e-02	(2.46±1.50)e+02	(4.34±2.80)e-01		*
8632	57.55±11.60	0.53±0.25	(2.15±0.83)e+01	(1.04±0.66)e-02	(1.97±0.76)e+01	(6.49±1.18)e-01	*	
8711	12.40±0.19	1.33±0.22	(6.33±3.33)e+01	(8.32±7.06)e-02	(5.93±2.93)e+01	(3.70±2.16)e-01		
8887	9.73±0.26	0.72±0.07	(2.75±1.16)e+01	(8.50±6.88)e-02	(2.60±1.01)e+01	(3.47±1.93)e-01		
9559	79.02±53.84	0.66±0.43	(7.41±1.46)e+01	(2.35±0.75)e-03	(6.72±1.32)e+01	(8.21±0.32)e-01	*	
9629	93.54±45.56	3.27±1.74	(6.70±6.31)e+02	(7.74±7.64)e-02	(6.94±6.94)e+04	(5.76±4.23)e-01		*
9661	67.26±4.42	1.12±0.02	(2.19±0.78)e+02	(2.10±1.10)e-03	(2.77±1.48)e+02	(8.57±0.71)e-01		*
10235	16.32±0.56	0.83±0.07	(2.78±0.40)e+01	(9.76±5.62)e-02	(2.69±0.31)e+01	(2.58±1.04)e-01	*	
10518	55.88±1.87	1.31±0.02	(3.10±0.61)e+01	(2.58±1.05)e-02	(2.87±0.53)e+01	(4.68±0.82)e-01	*	*
10689	17.64±0.66	0.66±0.04	(5.75±3.28)e+01	(7.49±5.79)e-03	(5.30±3.03)e+01	(7.14±1.37)e-01		
11218	7.45±0.15	0.98±0.05	(3.74±1.07)e+01	(8.98±6.40)e-02	(3.57±0.90)e+01	(3.03±1.49)e-01		

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
11387	169.84±109.47	1.79±1.33	(5.86±0.92)e+01	(3.27±1.16)e-02	(5.47±0.80)e+01	(4.20±0.72)e-01	*	*
11502	9.33±0.13	1.04±0.06	(4.13±1.36)e+01	(8.77±6.61)e-02	(3.92±1.16)e+01	(3.20±1.67)e-01		
11628	102.18±46.33	0.57±0.37	(4.43±1.08)e+01	(2.30±0.90)e-03	(4.04±0.99)e+01	(8.26±0.39)e-01	*	*
12281	16.84±0.56	0.29±0.05	(2.55±0.48)e+01	(2.75±0.85)e-03	(2.31±0.42)e+01	(8.05±0.33)e-01	*	
12308	119.56±63.20	1.19±0.85	(5.04±0.88)e+01	(6.14±1.85)e-03	(4.60±0.80)e+01	(7.06±0.45)e-01	*	*
12587	5.43±0.04	0.62±0.08	(1.70±0.81)e+01	(8.40±6.98)e-02	(1.60±0.71)e+01	(3.59±2.05)e-01		
12707	52.34±22.10	0.73±0.31	(1.92±0.38)e+01	(2.29±0.92)e-02	(1.78±0.33)e+01	(4.90±0.80)e-01	*	
12914	3.29±0.02	0.63±0.08	(2.05±0.63)e+01	(9.35±6.03)e-02	(1.96±0.54)e+01	(2.79±1.25)e-01		
12925	53.70±5.50	1.14±0.10	(4.63±2.31)e+01	(8.22±7.16)e-02	(4.34±2.02)e+01	(3.84±2.30)e-01		
13015	24.63±3.40	0.98±0.60	(1.91±1.83)e+02	(7.74±7.64)e-02	(2.00±2.00)e+04	(5.76±4.23)e-01		
13591	23.99±2.17	1.11±0.51	(2.75±2.56)e+02	(7.74±7.64)e-02	(2.84±2.84)e+04	(5.76±4.23)e-01		
13840	78.13±36.00	0.51±0.18	(3.78±1.94)e+01	(3.84±2.84)e-03	(5.18±3.50)e+01	(8.11±1.21)e-01	*	
14249	42.58±1.41	1.35±0.09	(9.35±5.45)e+01	(1.31±1.05)e-02	(8.59±4.97)e+01	(6.40±1.70)e-01		*
14380	46.19±11.22	0.82±0.13	(5.19±0.93)e+01	(7.59±2.40)e-03	(4.74±0.85)e+01	(6.75±0.51)e-01	*	
14622	24.59±1.55	1.05±0.18	(8.59±6.15)e+01	(1.06±0.91)e-02	(7.86±5.60)e+01	(6.82±1.78)e-01		*
14640	10.63±0.25	1.00±0.11	(3.03±1.33)e+01	(8.48±6.90)e-02	(2.85±1.15)e+01	(3.49±1.95)e-01		
14717	82.55±19.53	0.69±0.09	(8.87±1.73)e+01	(1.60±0.50)e-03	(8.09±1.56)e+01	(8.57±0.26)e-01	*	*
14733	53.34±2.48	1.48±0.02	(2.49±0.42)e+01	(5.35±2.43)e-02	(2.36±0.36)e+01	(3.36±0.93)e-01	*	*
14817	91.38±55.10	0.79±0.35	(1.49±0.43)e+01	(8.70±6.68)e-02	(1.42±0.36)e+01	(3.26±1.72)e-01	*	
15063	7.64±0.62	0.69±0.11	(1.84±0.94)e+01	(8.35±7.03)e-02	(1.72±0.83)e+01	(3.65±2.11)e-01		
15269	14.11±0.57	0.23±0.03	(1.96±0.18)e+01	(1.65±0.25)e-03	(1.77±0.18)e+01	(8.51±0.14)e-01	*	
15279	79.53±34.42	0.57±0.17	(1.67±0.66)e+01	(1.13±0.73)e-02	(1.52±0.59)e+01	(6.36±1.22)e-01	*	
15373	33.38±7.18	1.50±0.84	(3.70±3.50)e+02	(7.74±7.64)e-02	(3.85±3.84)e+04	(5.76±4.23)e-01		
15848	7.30±0.10	0.90±0.08	(5.04±2.66)e+01	(8.15±7.23)e-02	(4.70±2.32)e+01	(3.95±2.41)e-01		
15946	51.51±7.42	1.52±0.19	(5.39±3.08)e+01	(8.11±7.27)e-02	(5.02±2.70)e+01	(4.03±2.49)e-01		
16108	3.85±0.04	0.67±0.09	(1.25±0.52)e+01	(8.68±6.70)e-02	(1.19±0.45)e+01	(3.29±1.75)e-01		
16526	53.51±5.45	0.76±0.02	(3.92±2.33)e+01	(6.94±5.64)e-03	(3.62±2.15)e+01	(7.29±1.43)e-01		*
16863	29.17±2.83	0.35±0.12	(3.31±2.08)e+01	(2.25±1.25)e-03	(2.88±2.87)e+03	(8.88±1.11)e-01		
16901	49.77±7.17	0.83±0.04	(2.37±0.60)e+01	(1.94±0.93)e-02	(2.18±0.52)e+01	(5.27±0.96)e-01	*	
17238	142.89±98.77	2.26±1.81	(5.69±5.56)e+02	(7.74±7.64)e-02	(6.01±6.01)e+04	(5.76±4.23)e-01		
17321	9.51±0.16	1.12±0.06	(2.85±0.73)e+01	(9.22±6.16)e-02	(2.74±0.61)e+01	(2.87±1.33)e-01		
17476	52.03±3.04	0.99±0.06	(1.58±0.40)e+01	(8.89±6.49)e-02	(1.51±0.33)e+01	(3.10±1.56)e-01	*	
18067	20.09±0.64	0.34±0.02	(1.87±0.22)e+01	(7.04±1.45)e-03	(1.70±0.19)e+01	(6.83±0.31)e-01	*	
18301	139.82±70.02	3.10±1.92	(7.61±1.38)e+01	(9.78±3.19)e-03	(6.95±1.24)e+01	(6.35±0.56)e-01	*	*
18434	21.50±1.18	0.78±0.09	(1.07±0.14)e+01	(3.41±1.08)e-02	(1.00±0.13)e+01	(4.08±0.63)e-01	*	*
18467	71.02±39.31	0.88±0.35	(4.31±1.75)e+01	(1.91±1.32)e-02	(3.94±1.55)e+01	(5.58±1.49)e-01	*	
18840	19.66±1.52	0.88±0.32	(1.51±1.38)e+02	(7.74±7.64)e-02	(1.55±1.55)e+04	(5.76±4.23)e-01		
19516	8.76±0.06	0.38±0.01	(2.09±0.72)e+01	(2.00±1.00)e-03	(2.62±1.36)e+01	(8.61±0.66)e-01		*
19610	64.83±8.98	0.91±0.26	(3.59±0.52)e+01	(3.21±1.06)e-02	(3.36±0.45)e+01	(4.21±0.66)e-01	*	
19734	34.28±0.67	0.66±0.01	(1.62±0.54)e+01	(1.21±0.69)e-02	(1.48±0.48)e+01	(6.17±1.07)e-01	*	*
19763	19.22±4.53	0.35±0.07	(2.73±1.69)e+01	(3.35±2.35)e-03	(4.46±3.51)e+01	(8.28±1.15)e-01		
19780	78.43±31.49	1.92±0.45	(3.47±3.07)e+02	(7.74±7.64)e-02	(3.50±3.49)e+04	(5.76±4.23)e-01		
20206	17.54±0.55	2.07±0.06	(7.42±1.43)e+01	(9.55±5.83)e-02	(7.15±1.16)e+01	(2.68±1.14)e-01		*
20447	34.19±1.81	0.46±0.01	(2.02±0.47)e+01	(3.05±1.15)e-03	(1.85±0.43)e+01	(7.97±0.43)e-01	*	
20587	71.82±11.01	1.04±0.09	(2.42±0.84)e+01	(7.21±5.67)e-02	(2.29±0.72)e+01	(3.55±1.95)e-01	*	
21071	10.17±0.19	0.47±0.02	(1.35±0.77)e+01	(8.00±7.38)e-02	(1.25±0.68)e+01	(4.27±2.73)e-01		
22043	6.50±0.24	1.06±0.27	(6.47±4.35)e+01	(8.07±7.31)e-02	(6.01±3.89)e+01	(4.12±2.58)e-01		
22047	30.47±1.70	0.61±0.03	(1.27±0.14)e+01	(2.69±0.66)e-02	(1.19±0.13)e+01	(4.50±0.49)e-01	*	
22150	17.92±0.39	0.70±0.12	(1.32±0.30)e+01	(3.15±1.54)e-02	(1.23±0.27)e+01	(4.39±1.02)e-01	*	
22700	61.91±17.78	0.82±0.07	(5.27±1.02)e+01	(9.13±3.14)e-03	(4.81±0.91)e+01	(6.47±0.57)e-01	*	

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
23111	7.45±0.59	0.72±0.11	(2.05±1.24)e+01	(8.08±7.30)e-02	(1.91±1.10)e+01	(4.09±2.55)e-01		
23712	5.37±0.10	0.73±0.08	(1.89±0.58)e+01	(9.20±6.18)e-02	(1.81±0.50)e+01	(2.88±1.34)e-01		
23957	64.07±34.88	0.80±0.50	(2.10±0.41)e+01	(9.27±6.11)e-02	(2.02±0.33)e+01	(2.84±1.30)e-01	*	
24402	7.69±0.22	0.98±0.22	(3.63±1.98)e+01	(8.40±6.98)e-02	(3.40±1.76)e+01	(3.59±2.05)e-01		
24694	21.05±1.60	1.23±0.17	(4.39±1.71)e+01	(8.83±6.55)e-02	(4.16±1.48)e+01	(3.15±1.61)e-01		
25332	6.58±0.04	0.57±0.04	(8.22±4.04)e+00	(8.21±7.17)e-02	(7.70±3.53)e+00	(3.87±2.33)e-01		*
25707	160.38±91.81	2.35±1.85	(5.90±0.71)e+01	(1.01±0.53)e-01	(5.73±0.53)e+01	(2.44±0.90)e-01	*	
25916	39.74±0.08	2.71±0.01	(1.98±0.20)e+01	(2.99±0.68)e-02	(1.85±0.17)e+01	(4.28±0.44)e-01	*	*
26139	25.34±8.61	0.57±0.10	(1.24±0.16)e+01	(3.09±0.91)e-02	(1.16±0.14)e+01	(4.26±0.59)e-01	*	
26150	24.33±0.97	0.86±0.03	(1.19±0.13)e+01	(1.02±0.52)e-01	(1.16±0.10)e+01	(2.41±0.87)e-01	*	
26354	63.43±11.37	1.10±0.05	(5.77±1.13)e+01	(1.08±0.38)e-02	(5.26±0.99)e+01	(6.20±0.61)e-01	*	
27418	48.76±4.87	0.71±0.05	(8.81±2.87)e+01	(1.70±0.70)e-03	(1.36±0.82)e+02	(8.81±0.64)e-01		*
27883	50.87±5.18	0.52±0.07	(3.27±0.57)e+01	(3.79±1.10)e-03	(2.98±0.53)e+01	(7.69±0.37)e-01	*	
28331	50.51±8.86	2.07±0.76	(4.26±3.89)e+02	(7.74±7.64)e-02	(4.35±4.35)e+04	(5.76±4.23)e-01		
28922	11.77±0.18	2.26±0.32	(9.23±2.97)e+01	(9.34±6.04)e-02	(8.84±2.57)e+01	(2.79±1.26)e-01		*
29180	18.42±0.08	1.17±0.04	(2.19±0.97)e+01	(8.26±7.12)e-02	(2.06±0.84)e+01	(3.77±2.24)e-01		*
29514	81.39±19.88	1.73±0.87	(5.42±0.76)e+01	(3.40±1.11)e-02	(5.07±0.66)e+01	(4.10±0.66)e-01	*	
29526	61.62±5.93	1.12±0.02	(1.28±0.69)e+02	(4.99±3.79)e-03	(1.18±0.64)e+02	(7.62±1.16)e-01		*
31344	93.48±5.01	4.01±1.86	(2.67±0.34)e+02	(2.20±0.58)e-02	(2.47±0.30)e+02	(4.89±0.51)e-01	*	*
31359	6.41±0.10	1.04±0.13	(1.94±0.68)e+01	(9.00±6.38)e-02	(1.85±0.59)e+01	(3.02±1.48)e-01		
32141	7.63±0.16	0.57±0.04	(1.13±0.38)e+01	(8.77±6.61)e-02	(1.07±0.33)e+01	(3.20±1.67)e-01		
32679	6.15±0.35	1.12±0.27	(3.07±1.69)e+01	(8.44±6.94)e-02	(2.88±1.50)e+01	(3.54±2.00)e-01		
32775	32.19±2.91	0.42±0.14	(1.36±0.34)e+01	(6.89±2.89)e-03	(1.24±0.30)e+01	(6.93±0.65)e-01	*	
33105	7.84±0.32	0.95±0.40	(1.14±1.06)e+02	(7.74±7.64)e-02	(1.18±1.17)e+04	(5.76±4.23)e-01		
33723	85.53±87.64	1.84±1.34	(3.60±3.49)e+02	(7.74±7.64)e-02	(3.78±3.78)e+04	(5.76±4.23)e-01		
33745	26.52±6.69	0.86±0.19	(8.58±7.48)e+01	(4.23±4.13)e-02	(8.24±7.18)e+01	(5.63±3.32)e-01		
34243	55.73±4.01	0.71±0.07	(2.85±0.58)e+01	(1.15±0.43)e-02	(2.60±0.52)e+01	(6.11±0.66)e-01	*	
35277	23.61±1.44	1.54±0.11	(1.10±0.60)e+02	(8.08±7.30)e-02	(1.03±0.53)e+02	(4.08±2.55)e-01		
35420	44.49±5.01	0.53±0.02	(2.25±0.44)e+01	(7.79±2.69)e-03	(2.05±0.40)e+01	(6.72±0.56)e-01	*	
36882	46.74±4.77	0.60±0.04	(6.78±3.51)e+01	(3.20±2.20)e-03	(7.44±4.45)e+01	(8.16±0.95)e-01		
38198	5.74±0.09	0.70±0.09	(1.32±0.63)e+01	(8.40±6.98)e-02	(1.24±0.54)e+01	(3.58±2.04)e-01		
38764	69.16±38.17	0.73±0.26	(6.73±5.37)e+01	(6.39±5.39)e-03	(6.47±6.45)e+03	(7.98±2.01)e-01		
38826	43.18±3.46	1.17±0.05	(1.49±0.25)e+01	(9.53±5.85)e-02	(1.44±0.20)e+01	(2.69±1.15)e-01	*	
39197	21.84±1.29	0.65±0.09	(2.04±1.39)e+01	(2.15±1.87)e-02	(1.87±1.25)e+01	(5.84±2.17)e-01		
40248	10.84±0.24	0.41±0.02	(2.12±1.18)e+01	(6.84±5.24)e-03	(1.93±1.07)e+01	(7.24±1.31)e-01		
41434	5.78±0.07	0.48±0.06	(3.89±1.63)e+00	(8.61±6.77)e-02	(3.68±1.42)e+00	(3.35±1.81)e-01		
41461	23.03±1.73	1.29±0.59	(2.58±0.12)e+01	(1.16±0.38)e-01	(2.53±0.07)e+01	(1.99±0.45)e-01	*	
42252	5.12±0.05	0.67±0.06	(1.15±0.27)e+01	(9.67±5.71)e-02	(1.11±0.23)e+01	(2.62±1.08)e-01		
42411	19.48±2.39	1.40±0.49	(2.25±2.04)e+02	(7.74±7.64)e-02	(2.29±2.29)e+04	(5.76±4.23)e-01		
43248	8.53±0.32	0.81±0.26	(3.98±3.15)e+01	(7.88±7.50)e-02	(3.64±2.81)e+01	(4.58±3.04)e-01		
43326	7.71±0.14	0.54±0.05	(7.68±3.32)e+00	(8.45±6.93)e-02	(7.23±2.87)e+00	(3.53±1.99)e-01		
43341	91.34±9.41	0.65±0.02	(3.49±0.38)e+01	(4.04±0.75)e-03	(3.16±0.33)e+01	(7.59±0.23)e-01	*	*
43534	3.65±0.03	0.74±0.07	(1.71±0.61)e+01	(8.79±6.59)e-02	(1.62±0.53)e+01	(3.18±1.65)e-01		
44284	93.62±11.02	1.73±0.19	(7.10±4.71)e+01	(2.01±1.74)e-02	(6.55±4.30)e+01	(5.94±2.13)e-01		*
45900	33.26±1.92	0.64±0.04	(1.25±0.42)e+01	(1.67±1.00)e-02	(1.15±0.38)e+01	(5.67±1.21)e-01	*	
46303	88.97±34.80	0.83±0.22	(1.16±0.75)e+02	(3.15±2.15)e-03	(1.02±1.02)e+04	(8.61±1.38)e-01		
47211	54.00±12.41	0.57±0.04	(2.81±2.11)e+01	(1.28±1.18)e-02	(2.63±2.62)e+03	(7.30±2.69)e-01		
47530	45.61±16.60	0.66±0.23	(7.97±6.84)e+01	(1.41±1.31)e-02	(7.91±7.90)e+03	(7.20±2.79)e-01		
48685	14.95±1.05	0.79±0.05	(1.75±0.78)e+01	(8.31±7.07)e-02	(1.64±0.68)e+01	(3.70±2.17)e-01		
48833	46.79±2.51	1.06±0.05	(3.86±0.72)e+01	(1.04±0.35)e-02	(3.52±0.64)e+01	(6.26±0.58)e-01	*	*

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
48875	41.53±6.60	0.86±0.15	(2.51±1.60)e+01	(8.03±7.35)e-02	(2.32±1.42)e+01	(4.19±2.65)e-01		
49348	8.67±0.44	1.12±0.30	(3.32±2.02)e+01	(8.29±7.09)e-02	(3.10±1.80)e+01	(3.74±2.20)e-01		
49365	36.06±3.01	0.45±0.03	(1.52±0.25)e+01	(1.32±0.41)e-02	(1.39±0.23)e+01	(5.84±0.57)e-01	*	
49858	53.33±3.66	0.73±0.03	(2.06±0.98)e+01	(1.32±0.98)e-02	(1.87±0.87)e+01	(6.26±1.52)e-01	*	*
52260	17.21±0.86	0.53±0.07	(8.51±1.99)e+00	(5.75±3.42)e-02	(8.05±1.70)e+00	(3.43±1.28)e-01	*	
53245	47.59±17.39	1.46±0.66	(1.81±1.68)e+02	(7.74±7.64)e-02	(1.87±1.87)e+04	(5.76±4.23)e-01		
53843	26.78±5.29	0.47±0.17	(1.54±0.39)e+01	(1.41±0.65)e-02	(1.41±0.34)e+01	(5.82±0.87)e-01	*	
54415	62.50±14.37	0.76±0.09	(7.69±5.35)e+01	(1.03±0.89)e-02	(7.17±5.01)e+01	(6.88±1.80)e-01		
54601	71.04±8.48	2.57±1.76	(4.76±4.58)e+02	(7.74±7.64)e-02	(4.99±4.98)e+04	(5.76±4.23)e-01		*
54933	41.56±4.12	1.06±0.67	(2.40±0.06)e+01	(1.23±0.31)e-01	(2.37±0.03)e+01	(1.84±0.30)e-01	*	
55125	66.83±9.51	0.53±0.17	(2.38±0.58)e+01	(6.09±2.50)e-03	(2.17±0.53)e+01	(7.11±0.62)e-01	*	
55563	26.88±1.46	2.35±0.16	(1.82±0.75)e+02	(8.44±6.94)e-02	(1.71±0.65)e+02	(3.54±2.00)e-01		
57469	32.70±2.74	0.71±0.08	(1.20±0.31)e+01	(5.10±3.10)e-02	(1.13±0.27)e+01	(3.68±1.34)e-01	*	
58017	23.01±1.04	0.93±0.18	(3.10±2.09)e+01	(7.99±7.39)e-02	(2.86±1.84)e+01	(4.29±2.75)e-01		
59084	30.99±1.88	0.59±0.07	(6.05±3.88)e+01	(4.89±3.89)e-03	(5.31±5.29)e+03	(8.22±1.77)e-01		
60322	79.87±31.55	1.60±0.40	(8.66±2.23)e+01	(4.76±2.83)e-02	(8.14±1.92)e+01	(3.78±1.30)e-01	*	
61574	24.04±2.56	0.61±0.14	(4.37±3.86)e+01	(7.74±7.64)e-02	(4.40±4.39)e+03	(5.76±4.23)e-01		
61982	63.80±3.19	2.12±0.12	(8.49±4.26)e+01	(8.16±7.22)e-02	(7.93±3.71)e+01	(3.94±2.41)e-01		*
62321	22.20±3.87	0.97±0.09	(3.16±1.94)e+01	(7.99±7.39)e-02	(2.93±1.71)e+01	(4.29±2.75)e-01		*
62915	90.37±70.80	1.27±0.66	(3.90±0.46)e+01	(1.01±0.53)e-01	(3.79±0.35)e+01	(2.43±0.90)e-01	*	
63396	3.78±0.04	0.56±0.07	(7.11±2.59)e+00	(8.91±6.47)e-02	(6.76±2.24)e+00	(3.09±1.55)e-01		
65359	38.44±4.29	1.35±0.57	(1.55±1.43)e+02	(7.74±7.64)e-02	(1.59±1.59)e+04	(5.76±4.23)e-01		
66266	49.36±7.69	0.93±0.21	(1.20±0.11)e+01	(1.06±0.48)e-01	(1.17±0.08)e+01	(2.26±0.73)e-01	*	
67170	86.76±56.40	2.44±1.51	(5.56±5.30)e+02	(7.74±7.64)e-02	(5.80±5.80)e+04	(5.76±4.23)e-01		
68006	7.61±0.19	0.66±0.14	(1.34±0.86)e+01	(8.09±7.29)e-02	(1.25±0.76)e+01	(4.07±2.53)e-01		
68304	19.16±0.91	1.10±0.43	(2.51±0.02)e+01	(1.35±0.19)e-01	(2.49±0.01)e+01	(1.65±0.11)e-01	*	
69017	8.32±0.09	0.55±0.06	(1.24±0.63)e+01	(8.23±7.15)e-02	(1.16±0.55)e+01	(3.82±2.29)e-01		
69020	66.65±9.69	3.16±1.71	(6.16±5.80)e+02	(7.74±7.64)e-02	(6.39±6.38)e+04	(5.76±4.23)e-01		
70045	6.64±0.20	1.16±0.15	(3.97±1.68)e+01	(8.61±6.77)e-02	(3.75±1.46)e+01	(3.35±1.81)e-01		*
70961	8.11±0.36	0.83±0.20	(2.26±1.28)e+01	(8.38±7.00)e-02	(2.12±1.13)e+01	(3.62±2.08)e-01		
71682	9.79±0.31	0.78±0.30	(8.48±7.77)e+01	(7.74±7.64)e-02	(8.68±8.67)e+03	(5.76±4.23)e-01		
71695	18.24±0.67	1.25±0.61	(2.06±1.92)e+02	(7.74±7.64)e-02	(2.13±2.12)e+04	(5.76±4.23)e-01		
71704	4.36±0.05	0.61±0.08	(1.71±0.73)e+01	(8.60±6.78)e-02	(1.61±0.63)e+01	(3.36±1.82)e-01		
71837	17.57±1.17	0.78±0.35	(6.33±5.87)e+01	(7.74±7.64)e-02	(6.51±6.51)e+03	(5.76±4.23)e-01		
72039	47.79±5.68	0.89±0.12	(3.48±2.55)e+01	(2.35±2.14)e-02	(3.18±2.29)e+01	(5.87±2.42)e-01		
72114	5.44±0.07	0.49±0.06	(9.07±4.77)e+00	(8.22±7.16)e-02	(8.48±4.18)e+00	(3.84±2.30)e-01		
73691	38.66±18.73	1.16±0.51	(3.40±0.47)e+01	(3.77±1.26)e-02	(3.19±0.41)e+01	(3.90±0.67)e-01	*	
73958	69.31±30.90	1.15±0.13	(5.17±0.72)e+01	(1.34±0.35)e-02	(4.75±0.64)e+01	(5.79±0.48)e-01	*	
75675	50.52±4.18	0.73±0.04	(3.48±2.05)e+01	(1.51±1.24)e-02	(3.19±1.86)e+01	(6.23±1.82)e-01		
77865	64.72±116.53	3.15±1.09	(4.84±4.40)e+02	(7.74±7.64)e-02	(4.94±4.93)e+04	(5.76±4.23)e-01		*
78754	18.85±0.70	0.23±0.03	(2.16±0.39)e+01	(1.40±0.40)e-03	(2.08±0.43)e+01	(8.72±0.25)e-01	*	
80343	28.35±1.66	0.65±0.07	(3.13±2.24)e+01	(7.80±7.58)e-02	(2.89±2.00)e+01	(4.88±3.34)e-01	*	
81399	86.30±75.68	1.42±0.86	(2.75±2.62)e+02	(7.74±7.64)e-02	(2.87±2.86)e+04	(5.76±4.23)e-01		
81407	19.62±2.23	0.80±0.35	(1.17±0.04)e+01	(1.20±0.33)e-01	(1.15±0.02)e+01	(1.89±0.35)e-01	*	
82528	68.75±15.33	1.10±0.07	(2.78±0.77)e+01	(8.76±6.62)e-02	(2.65±0.64)e+01	(3.21±1.67)e-01	*	
84052	20.74±0.52	1.85±0.11	(4.79±1.16)e+01	(9.37±6.01)e-02	(4.61±0.97)e+01	(2.77±1.24)e-01		
85306	10.67±0.51	0.97±0.09	(1.47±0.73)e+01	(8.25±7.13)e-02	(1.38±0.63)e+01	(3.80±2.26)e-01		*
85505	72.41±18.05	1.04±0.55	(4.28±0.63)e+01	(1.37±0.38)e-02	(3.93±0.56)e+01	(5.76±0.51)e-01	*	
85563	25.95±9.10	0.88±0.24	(8.53±0.80)e+00	(1.04±0.49)e-01	(8.31±0.59)e+00	(2.30±0.76)e-01	*	*
85608	36.68±6.43	1.58±0.75	(2.44±2.28)e+02	(7.74±7.64)e-02	(2.52±2.52)e+04	(5.76±4.23)e-01		

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
85714	109.78±14.96	0.58±0.06	(4.46±1.96)e+01	(2.90±1.90)e-03	(4.31±2.02)e+01	(8.17±0.80)e-01	*	
87719	29.26±2.51	0.97±0.59	(1.23±1.18)e+02	(7.74±7.64)e-02	(1.29±1.29)e+04	(5.76±4.23)e-01		
87816	95.58±104.75	1.66±1.23	(3.30±3.20)e+02	(7.74±7.64)e-02	(3.47±3.47)e+04	(5.76±4.23)e-01		
88109	154.58±83.75	2.84±1.90	(4.72±4.54)e+02	(7.74±7.64)e-02	(4.94±4.94)e+04	(5.76±4.23)e-01		*
88125	38.83±3.24	0.48±0.05	(3.36±1.33)e+01	(4.64±2.84)e-03	(3.09±1.23)e+01	(7.59±0.87)e-01	*	
88538	17.80±0.79	0.86±0.07	(2.48±1.34)e+01	(8.11±7.27)e-02	(2.31±1.17)e+01	(4.03±2.49)e-01		
88764	61.82±15.26	1.06±0.22	(1.98±0.38)e+01	(9.32±6.06)e-02	(1.90±0.30)e+01	(2.81±1.27)e-01	*	
89204	57.19±7.94	0.70±0.05	(1.64±0.41)e+01	(3.30±1.75)e-02	(1.53±0.36)e+01	(4.35±1.12)e-01	*	
90559	12.73±0.36	0.77±0.09	(2.12±1.24)e+01	(8.07±7.31)e-02	(1.97±1.09)e+01	(4.12±2.58)e-01		
90719	16.10±0.75	0.61±0.19	(6.08±5.47)e+01	(7.74±7.64)e-02	(6.17±6.16)e+03	(5.76±4.23)e-01		
91844	64.74±39.51	1.44±0.93	(2.43±2.33)e+02	(7.74±7.64)e-02	(2.54±2.54)e+04	(5.76±4.23)e-01		
93070	56.97±12.08	0.68±0.06	(4.88±3.27)e+01	(6.44±5.44)e-03	(4.41±2.94)e+01	(7.42±1.46)e-01		*
93240	29.14±10.91	1.31±0.24	(1.02±0.89)e+02	(7.74±7.64)e-02	(1.02±1.02)e+04	(5.76±4.23)e-01		
93244	10.02±0.25	0.65±0.06	(1.47±0.75)e+01	(8.20±7.18)e-02	(1.37±0.65)e+01	(3.87±2.34)e-01		
96237	64.01±32.63	1.73±1.09	(3.00±2.87)e+02	(7.74±7.64)e-02	(3.13±3.13)e+04	(5.76±4.23)e-01		
98706	3.14±0.03	0.72±0.11	(1.18±0.40)e+01	(9.26±6.12)e-02	(1.13±0.35)e+01	(2.84±1.30)e-01		
100244	100.71±49.58	2.96±1.78	(2.94±2.80)e+02	(7.74±7.64)e-02	(3.07±3.06)e+04	(5.76±4.23)e-01		*
101866	11.27±0.20	0.57±0.06	(9.83±6.07)e+00	(7.99±7.39)e-02	(9.12±5.36)e+00	(4.28±2.74)e-01		
103358	55.49±19.23	1.96±0.24	(5.45±3.25)e+01	(8.05±7.33)e-02	(5.06±2.86)e+01	(4.15±2.61)e-01		
106622	8.13±0.26	0.71±0.04	(1.14±0.49)e+01	(8.36±7.02)e-02	(1.07±0.42)e+01	(3.64±2.10)e-01		
111676	17.49±0.90	1.08±0.53	(1.62±1.52)e+02	(7.74±7.64)e-02	(1.68±1.68)e+04	(5.76±4.23)e-01		
111682	8.72±0.19	0.98±0.35	(1.27±1.16)e+02	(7.74±7.64)e-02	(1.30±1.30)e+04	(5.76±4.23)e-01		
115321	25.39±1.56	0.93±0.09	(5.86±3.73)e+01	(2.68±2.32)e-02	(5.35±3.33)e+01	(5.48±2.23)e-01		
115664	47.81±5.94	1.48±0.14	(2.88±0.03)e+01	(1.32±0.22)e-01	(2.85±0.01)e+01	(1.69±0.16)e-01	*	
119012	294.57±279.62	4.50±2.23	(3.02±2.83)e+02	(7.74±7.64)e-02	(3.12±3.12)e+04	(5.76±4.23)e-01		*
121297	33.57±4.89	1.60±0.43	(1.08±0.87)e+02	(7.84±7.54)e-02	(9.94±7.76)e+01	(4.73±3.20)e-01		
126167	37.20±2.92	1.44±0.04	(3.63±2.11)e+01	(5.01±4.49)e-02	(3.34±1.86)e+01	(4.67±2.57)e-01		*
127732	112.77±120.02	2.10±1.42	(3.18±3.06)e+02	(7.74±7.64)e-02	(3.33±3.33)e+04	(5.76±4.23)e-01		
128898	97.78±48.80	4.96±1.59	(5.70±5.15)e+02	(7.74±7.64)e-02	(5.79±5.79)e+04	(5.76±4.23)e-01		*
132692	10.47±0.54	0.59±0.10	(1.57±1.04)e+01	(7.98±7.40)e-02	(1.46±0.93)e+01	(4.31±2.77)e-01		
133648	38.41±5.04	1.79±0.18	(3.48±1.28)e+01	(8.77±6.61)e-02	(3.30±1.10)e+01	(3.20±1.66)e-01		
134282	15.81±1.15	0.78±0.30	(9.74±8.92)e+01	(7.74±7.64)e-02	(9.97±9.96)e+03	(5.76±4.23)e-01		
136289	103.47±50.83	1.58±1.18	(1.76±1.71)e+02	(7.74±7.64)e-02	(1.85±1.85)e+04	(5.76±4.23)e-01		*
137806	9.05±0.24	0.90±0.04	(1.21±0.33)e+01	(9.05±6.33)e-02	(1.15±0.27)e+01	(2.98±1.44)e-01		
137900	21.40±1.34	1.60±0.49	(7.30±5.71)e+01	(7.89±7.49)e-02	(6.73±5.14)e+01	(4.57±3.03)e-01		
138629	14.15±0.46	1.35±0.61	(1.95±1.81)e+02	(7.74±7.64)e-02	(2.01±2.01)e+04	(5.76±4.23)e-01		
142549	19.90±1.57	1.85±0.53	(5.84±4.11)e+01	(8.03±7.35)e-02	(5.39±3.66)e+01	(4.19±2.65)e-01		
143129	70.14±64.74	1.46±1.01	(1.77±1.70)e+02	(7.74±7.64)e-02	(1.85±1.85)e+04	(5.76±4.23)e-01		
143712	33.92±3.92	1.15±0.65	(1.53±1.45)e+02	(7.74±7.64)e-02	(1.59±1.59)e+04	(5.76±4.23)e-01		
144313	8.46±0.28	1.02±0.14	(1.49±0.60)e+01	(8.76±6.62)e-02	(1.41±0.52)e+01	(3.21±1.67)e-01		
149120	28.03±0.55	1.00±0.02	(1.39±0.65)e+01	(8.17±7.21)e-02	(1.30±0.56)e+01	(3.92±2.38)e-01		
154728	21.67±1.47	0.99±0.12	(1.90±0.88)e+01	(8.42±6.96)e-02	(1.79±0.77)e+01	(3.57±2.03)e-01		
154963	25.90±2.90	1.08±0.67	(1.54±1.47)e+02	(7.74±7.64)e-02	(1.61±1.61)e+04	(5.76±4.23)e-01		
157113	8.37±0.26	0.62±0.11	(1.01±0.54)e+01	(8.33±7.05)e-02	(9.49±4.73)e+00	(3.67±2.14)e-01		
160293	6.66±0.15	0.52±0.04	(8.32±3.91)e+00	(8.28±7.10)e-02	(7.80±3.39)e+00	(3.75±2.21)e-01		
162704	18.91±1.27	0.88±0.41	(6.82±6.34)e+01	(7.74±7.64)e-02	(7.03±7.02)e+03	(5.76±4.23)e-01		
177649	8.17±0.15	0.65±0.15	(1.05±0.66)e+01	(8.15±7.23)e-02	(9.75±5.82)e+00	(3.96±2.42)e-01		
178528	8.61±0.24	1.33±0.11	(2.53±0.65)e+01	(9.41±5.97)e-02	(2.43±0.55)e+01	(2.75±1.21)e-01		
178695	51.82±8.94	1.06±0.34	(1.09±0.99)e+02	(7.74±7.64)e-02	(1.11±1.11)e+04	(5.76±4.23)e-01		
178811	10.39±0.34	0.84±0.13	(1.03±0.44)e+01	(8.72±6.66)e-02	(9.76±3.80)e+00	(3.24±1.70)e-01		

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Table continued.

ID	Wobble period(h)	Wobble amplitude (mas)	Separation (km) 1st interval	Mass ratio 1st interval	Separation (km) 2nd interval	Mass ratio 2nd interval	Taxonomy correction	$\widehat{\text{SNR}} > 1$
179462	25.59±4.20	1.12±0.54	(1.95±0.07)e+01	(1.19±0.35)e-01	(1.92±0.04)e+01	(1.92±0.38)e-01	*	
191158	15.00±0.23	0.68±0.06	(5.40±0.13)e+00	(1.24±0.30)e-01	(5.34±0.07)e+00	(1.82±0.28)e-01	*	
196138	10.04±0.30	1.25±0.15	(2.69±1.00)e+01	(8.83±6.55)e-02	(2.55±0.87)e+01	(3.14±1.61)e-01		
196980	12.81±0.36	1.21±0.17	(2.83±0.99)e+01	(9.10±6.28)e-02	(2.70±0.86)e+01	(2.94±1.40)e-01		
207051	29.75±2.89	0.83±0.34	(9.53±0.37)e+00	(1.18±0.36)e-01	(9.38±0.22)e+00	(1.94±0.40)e-01	*	
207591	41.75±5.86	1.75±0.23	(3.83±0.78)e+01	(9.22±6.16)e-02	(3.68±0.62)e+01	(2.86±1.33)e-01	*	
209519	18.39±0.72	0.54±0.06	(5.22±1.36)e+00	(5.87±3.75)e-02	(4.92±1.15)e+00	(3.48±1.41)e-01	*	
213095	19.23±2.51	1.81±0.18	(3.82±1.11)e+01	(9.27±6.11)e-02	(3.66±0.95)e+01	(2.83±1.30)e-01		
249603	27.36±5.30	0.67±0.05	(3.56±2.71)e+01	(1.42±1.32)e-02	(3.35±3.34)e+03	(7.20±2.79)e-01		
251949	68.89±48.29	1.47±0.75	(2.48±2.33)e+02	(7.74±7.64)e-02	(2.57±2.57)e+04	(5.76±4.23)e-01		
254559	18.92±3.27	1.12±0.30	(3.20±2.44)e+01	(7.89±7.49)e-02	(2.95±2.19)e+01	(4.55±3.01)e-01		
255299	23.67±2.14	1.10±0.16	(2.19±0.73)e+01	(8.52±6.86)e-02	(2.07±0.61)e+01	(3.44±1.91)e-01	*	
264981	184.93±47.19	2.52±0.78	(1.50±1.35)e+02	(7.74±7.64)e-02	(1.52±1.52)e+04	(5.76±4.23)e-01		*
268230	37.36±9.30	1.27±0.77	(1.74±1.66)e+02	(7.74±7.64)e-02	(1.82±1.81)e+04	(5.76±4.23)e-01		
271047	10.21±0.21	0.71±0.10	(8.09±3.57)e+00	(8.57±6.81)e-02	(7.63±3.11)e+00	(3.39±1.85)e-01		
285353	25.19±3.74	1.08±0.51	(8.82±8.21)e+01	(7.74±7.64)e-02	(9.10±9.09)e+03	(5.76±4.23)e-01		
289599	14.68±0.50	0.39±0.03	(6.66±1.72)e+00	(2.75±1.44)e-02	(6.18±1.51)e+00	(4.68±1.09)e-01	*	
299198	52.61±14.89	1.64±0.21	(3.43±2.07)e+01	(8.05±7.33)e-02	(3.18±1.82)e+01	(4.15±2.62)e-01		
331792	15.71±0.04	0.82±0.01	(8.17±2.44)e+00	(8.72±6.66)e-02	(7.77±2.04)e+00	(3.25±1.71)e-01		*

4.3 Comments and Future steps

The paper presented in the previous section is in the final adjustments before the submission to the *Astronomy and Astrophysics* journal. It is the result of extensive work which started during my 1-year stay at Observatoire de la Cote d’Azur under the supervision of Dr. Paolo Tanga.

We develop a method to retrieve the astrometric signal from Gaia observations and, after a careful blind search and several processes of validation and filtering, we provide a list of the best binary candidates with strong detections, dynamical characteristics and physical properties that best fit the binary system hypothesis.

In this work, we use the Generalized Lomb-Scargle periodogram implemented with the *ASTROPY* package ([Astropy Collaboration et al., 2013, 2018, 2022](#); [VanderPlas, 2018](#)). It was very useful and provided us with good results in a reasonable time. However, it is not possible to have access to the source code of this package which limits our understanding and control over this part of the process. Therefore, the next step will be to code an implementation of the Generalized Lomb-Scargle periodogram from scratch in order to have full control over all of the processes in our method of detection and selection of astrometric binary asteroids.

Another important aspect that will be taken into account in the future, among the others mentioned in the paper, is the geometric corrections in the Gaia observations. For the moment, we use only short windows of time with consecutive Gaia observations. Under these conditions, the geometric configuration of the observation can be assumed to be unchanged as a first approximation. However, from one transit to another, the observation conditions are different. At each transit, there are several variations which are neglected at the moment. The relative positions between the object and the Gaia satellite, the illuminated area of the target’s surface, and the change in the observed surface due to the object’s rotation, are some of the corrections we aim to apply in the following versions of the method. In these cases, we may be missing significant data by not using the observations spread over longer periods. Hence, with these improvements, we expect to be able to use longer sequences of observations to retrieve astrometric signals and detect new binary candidates.

Additionally, as discussed in the paper, we present a series of pieces of evidence that our list of candidates may contain several binary asteroids first detected using only astrometric data. However, we still need confirmation of these candidates from other observation techniques. Most of the candidates in our list are probably too far to be detected with radar observations, too small to be detected using photometric lightcurve, and the binary components are too close to each other to be resolved by direct imaging. Therefore, one of the best techniques to detect this type of celestial object is probably the stellar occultation. These are solar eclipse-like events where there is a perfect alignment between the observer, the target and a background source of light. It happens when an object passes in front of a star and occults it to the observer. Since the star is a beam of light with approximately parallel light rays, the shadow of the object over the Earth’s surface has nearly the same size and shape as the occulting object. This powerful technique, combined ultra-high precision data on stars’ positions from Gaia DR3, has allowed not

only the determination of the size, shape and position of the targets, but also surface features and the presence of material in the surroundings of the body, such as atmosphere, rings, and satellites (Sicardy et al., 2006; Braga-Ribas et al., 2014; Leiva et al., 2020; Rommel et al., 2022; Gault et al., 2022; Morgado et al., 2023; Pereira et al., 2023).

Therefore, once the paper is published, the GaiaMoons team¹ will work along with the scientific community to observe the objects in our list of binary candidates, through stellar occultation campaigns promoted by the ACROSS team², in order to detect the satellites and obtain confirmation of the binary nature to some of our astrometric candidates.

¹ <https://lagrange.oca.eu/fr/gaiamoons>

² <https://lagrange.oca.eu/fr/home-across>

5 Conclusions

The Solar System is filled with a variety of minor bodies with all sorts of physical and dynamical properties. Each one of them tells a different part of the story of planetary evolution, so it is important to study these objects so that we can have more information to understand the processes of formation and evolution of objects in the Sun's backyard. Therefore, in this research, we aimed to study the evolution, transport and detection of minor objects in the Solar System.

We revised some aspects of the Near-Earth Objects' dynamics and presented a detailed analysis of the evolution of a population of 985 large known NEOs where we studied their lifetimes, the transitions among the different minor bodies regions of the Solar System, the role of the inclination on the evolution of this population, the characteristics of the objects that impact the planets and some preliminary results on the population in the inner Venus zone.

When analysing the lifetimes, we found that following the same approach as in [Gladman et al. \(2000\)](#) we obtained a median dynamical lifetime for the large NEO population similar to their results, of about 10 Myrs. However, we showed that thermal disruption is the most efficient mechanism to dump objects from the NEO region, being the end for more than 80% of the studied bodies. Additionally, this population have a significant contribution to the extra-solar objects, where 13% of their orbits turn into hyperbolic and therefore are ejected from the Solar System.

We found that the most common route for NEOs to take in the Solar System is to move to the JFC region, then get thrown into the Sun's direction due to the strong perturbations from Jupiter and end up being destroyed by the thermal effects. Of the 839 objects in the filtered sample, almost 60% of them were first transferred to the JFC region and 77% of the objects were lastly inside it before reaching their fates.

We showed that 14% of the objects never leave the NEO region and are the main source of collisions with the planets and survivors. Meanwhile, the MAB region seems to be a transitional region for NEOs since almost 35% of the objects are transferred into it, but only 0.5% end their lives inside the MAB region.

We also showed that almost 10% of the large known NEOs studied reached the CEN region and, even though most of the objects are eliminated from the region in a short timescale, some of them remained as a centaur for a few hundred thousand years. It is evidence that there is a possibility one could find centaurs today that were once NEO.

Looking at the whole sample of 985 objects in the known large NEO population, we found that they tend to have an increase in the median orbital inclinations by a factor of approximately 1.7 due to the typical perturbations from the planets, especially close encounters. These variations are usually smaller than 20° , but we found that more than 1/4 of the population experiences larger variations, and 10% can evolve into retrograde orbits while having initially prograde orbits.

The variations in inclination tend to be small and the significant difference at the

end of their lives is due to a smooth and cumulative process, instead of a singular strong event that causes a large delta in their orbital inclination. We show that inclinations are an important factor that rules the lifetime of objects in the NEO region. Over time, the objects tend to evolve to values of inclination between 20° and 50° , which seems to be the most stable configuration for long-lived NEOs.

Objects with initially low or high inclinations and retrograde orbits that do not evolve into the "safe range" of intermediate inclinations, tend to have shorter lifetimes. Objects with high inclinations ($i > 60^\circ$) usually end in ejection from the Solar System or thermal disruption while on the way to hit the Sun, while objects with low inclinations tend to collide with planets in short timescales.

None of the studied NEOs with initial inclinations smaller than 20° survived more than 20 Myrs, except for those that evolved into the intermediate range of inclinations. The only objects that survived more than 60 Myrs are those that had initial inclinations in the "safe range", or evolved into it. Therefore, objects in the large NEO population are probably new arrivals from the Main belt, while those with intermediate inclinations have probably been in the terrestrial region for at least 20 Myrs, and will remain for much longer periods of time.

Additionally, we were able to obtain a frequency of km-size NEO impact on Mercury, Venus and Earth, which are the planets suffering more than 80% of the collisions with NEOs. Even though the objects with low inclinations represent a threat for their faster collision timescales, the objects with intermediate inclinations also present a constant high risk of impact with an occurrence frequency of one highly energetic collision with the Earth each $\sim 200,000$ years, consistent with the expected values from the literature, and $\sim 120,000$ years with Venus, in a steady state scenario.

Furthermore, we showed that the gravitational perturbation from the planets is enough to send part of the NEO population into orbits internal to Venus and even Mercury. Our results indicate that objects that eventually become Matiras usually present $a > 1.3$, pericenters between Venus and Mars, and apocenter between Mars and Jupiter; while those that become Vatiras are initially more scattered in the NEO region.

We found that it is very unlikely that there is a population of km-size objects in the inner Mercury zone composed of former NEOs. If there is such a population, it is probably the primordial Vulcanoids that are reminiscent of the planets' formation period. Meanwhile, $\sim 2.5\%$ of the studied bodies became Vatiras and presented significantly long lifetimes and residence times inside the zone. Additionally, Vatiras present a 50% chance of hitting Venus or Earth and more than 14% of a chance to survive. It suggests that even though there is only one example of Vatira detected so far, this population of objects may exist and present a significant risk for our planet, so they must be found and tracked closely.

In this thesis, it was also explored the detection of binary asteroids using Gaia DR3 astrometric data. Asteroids with satellites are an excellent sample of objects for studying the collisions and dynamical evolution of minor bodies. The currently known binary population is limited to ~ 500 objects that were discovered through a variety of techniques that produce distributions with significant observational bias, especially for objects in the intermediate-sized asteroid range (approximately 20–100 km). In this

case, the satellites are hardly detectable with the usual techniques, such as photometric observation of mutual events and direct imaging with adaptative optics.

Therefore, we developed a completely independent binary asteroid discovery technique based only on astrometric data from Gaia DR3, which can help to discover new binary asteroid systems in configurations not much explored yet due to the current instrument limitations.

Using the generalized Lomb-Scargle periodogram we looked for periodicities in the asteroid's astrometric data. The statistical selection performed with Monte Carlo simulations on the detections obtained from the periodogram allowed us to remove the cases that presented a higher probability of false detection. Then, with a series of filterings based on the physical and dynamic properties of the objects, we obtained a list of 67 binary candidates.

The presence of known binaries in our list of detections; the fact that part of our candidates matches the properties of the known population of small binaries; the taxonomic over-representation of S-types is consistent with the observations; and the fact that some of our binary candidates are possibly synchronous binaries which are rarely discovered by photometric lightcurve. These are some of the pieces of evidence that indicate that our method is successful at retrieving the astrometric signal in Gaia DR3 asteroids' data. However, further confirmation of our astrometric binary candidates will be obtained in the future with other observation techniques.

Finally, this thesis presented extensive work on different topics of study about the minor bodies in the solar system that extend from celestial mechanics to the development of a new observational detection method. Through the new results and discussions presented here, we believe this work will have a positive impact on various topics of study about the Solar System's minor bodies.

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