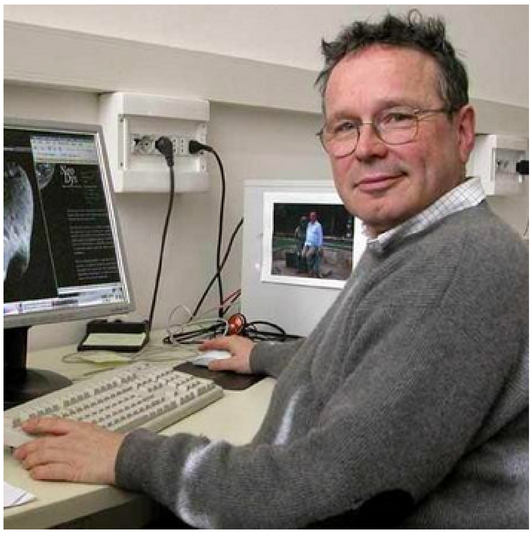
Dynamics and physics in the solar system: the legacy of Paolo Farinella and Andrea Milani Pisa (Italy), 18-21 June 2024 Information and abstracts

Prof. Paolo Farinella (1953-2000) and Prof. Andrea Milani (1948-2018) developed outstanding research at the University of Pisa, in the field of physics and dynamics of natural and artificial celestial bodies. Their work had a deep influence in the understanding of the dynamics of the small bodies of the Solar System, of the motion of planetary satellites and of the application to the exploration of planetary bodies through space missions. This conference, devoted to their memory, will bring together experts in physics and dynamics of celestial bodies, and will highlight Paolo and Andrea's heritage into the new generation of researchers in their area of knowledge.

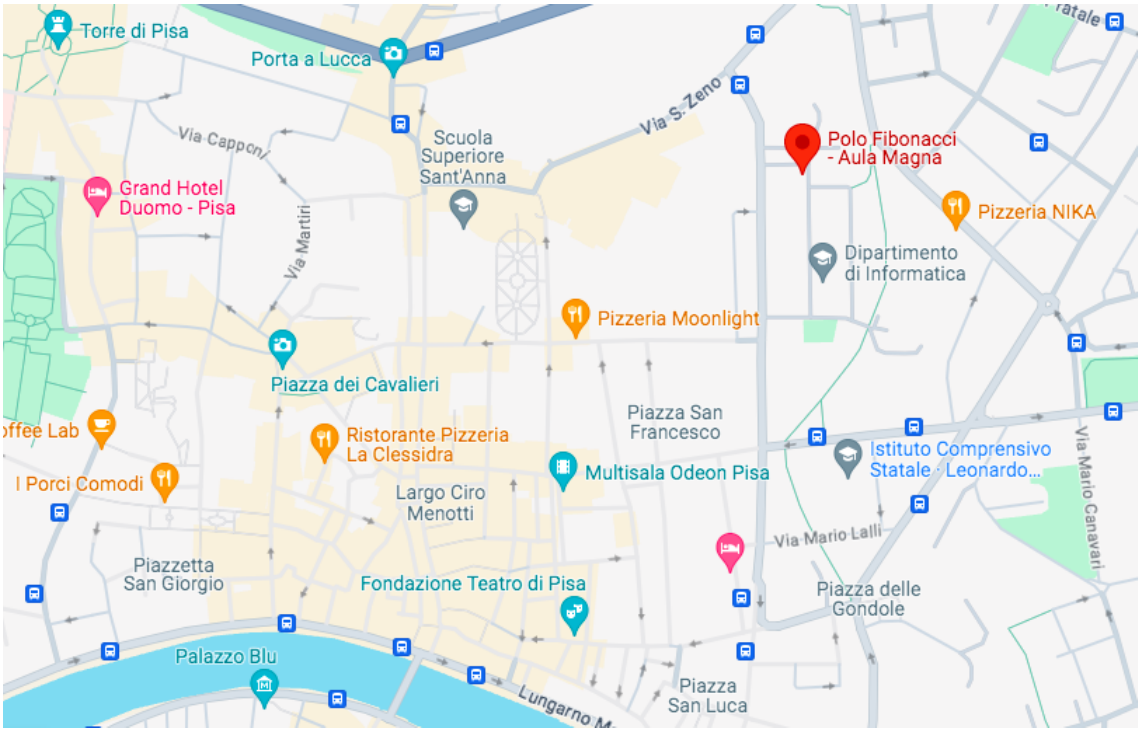
Paolo Farinella (1953-2000)



Andrea Milani (1948-2018)

Venue

The conference will take place in the "Aula Magna" of "Polo Fibonacci", Largo Bruno Pontecorvo 3, 56127 Pisa (building E). The "Polo Fibonacci" is near the Department of Mathematics of the University of Pisa.
The building is highlighted in the following map:



Dynamics and Physics in the Solar System – The Legacy of Paolo Farinella and Andrea Milani

PROGRAM

	TUE 18 JUNE	WED 19 JUNE	THU 20 JUNE	FRI 21 JUNE
8:00-9:00	Registration	Registration	Registration	
9:00-9:30	Welcome	MARCHI	KNEZEVIC	BIANCO
9:30-10:00	SPOTO	DERMOTT	LASKAR	BERNARDI
10:00-10:20	GRANVIK	SCHEERES	TSIRVOULIS	USPID
10:20-10:40	FAGGIOLI	AGRUSA	PILAT-LOHINGER	CALIMAN COURTOT
10:40-10:50	FENUCCI	ALNAJJARINE	ZIMMERMANN	RODRIGUEZ
10:50-11:00	VAVILOV	BOUGAKOV	LIPPI	VOVK
11:00-11:30	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK
11:30-12:00	VOKROUHLICKY	MIGNARD	BOTTKE	NOBILI
12:00-12:20	FERRAZ-MELLO	TANGA	CORREIA	CHIOFALO
12:20-12:40	 LIBERATO	FUENTES-MUNOZ	SAILLENFEST	PUCACCO MARIANI
12:40-13:00	MARO'	BALOSSI KOSHERBAYEVA	GOMES ZOPETTI	HEISSEL CONCLUSIONS
13:00-14:30	LUNCH	LUNCH	LUNCH	
14:30-15:00	CELLETTI	CHESLEY	TSIGANIS	
15:00-15:30	FARNOCCHIA	CAMPO-BAGATIN ZHOU	LEGNARO GIRALT	
15:30-15:50	GRONCHI	KANAMARU	BENET	
15:50-16:10	GRASSI MAKADIA	MOCHI PAOLI	CICALO'	
16:10-16:20	GUZZO	LIU	VOYATZIS	
16:20-16:30		MAGNANINI	DOGKAS	
16:30-17:00	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK	
17:00-17:30	PINZARI MASTROIANNI ROSSI	MICHEL	DAVIS	
17:30-17:50	DI RUZZA POLIMENI	LASAGNI-MANGHI	VARTOLOMEI CARBOGNANI	
17:50-18:00	ASSAN	TOLIOU	ALMEIDA	
		SOCIAL DINNER 20:00-22:30		

LEGEND:

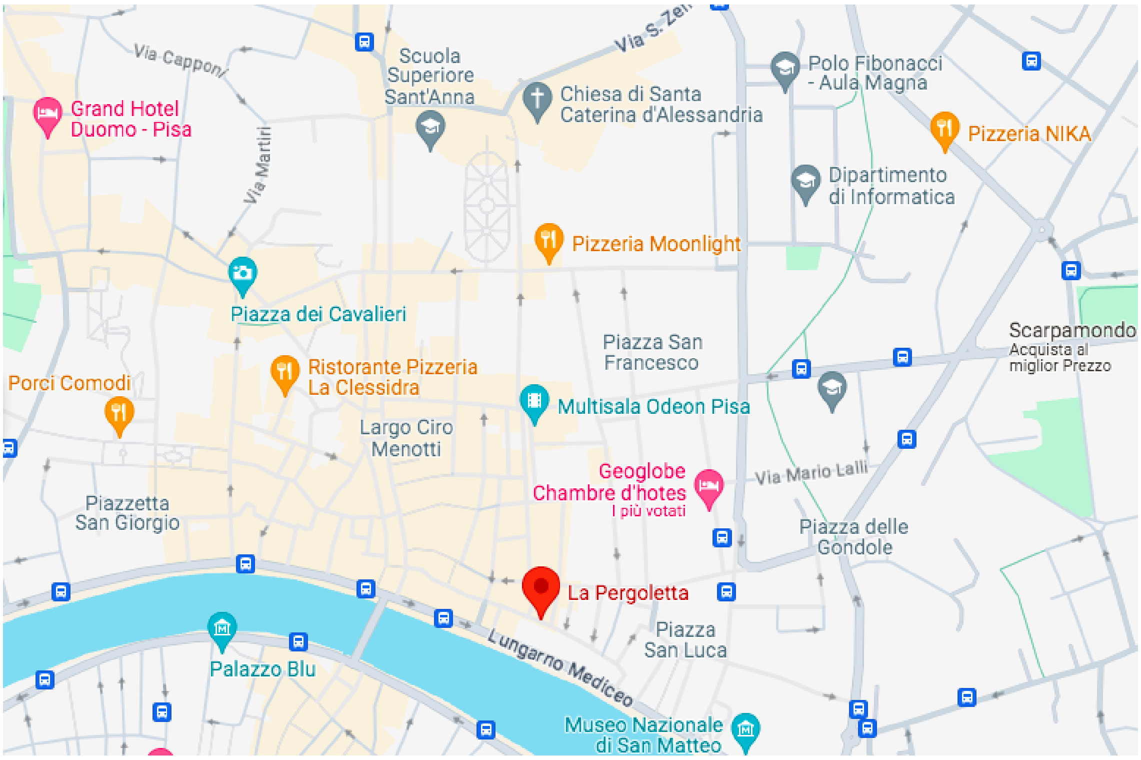
INVITED (30 min)

CONTRIBUTED LONG (20 min)

CONTRIBUTED SHORT (10 min)

Social dinner

The conference dinner will take place at the "La Pergoletta" restaurant (www.ristorantelapergoletta.com), Via delle belle Torri 40, on **Wednesday 19 June at 8 pm**.
The following map shows the location of the restaurant.



Abstracts

Authors: *Agrusa H. F.*, Walsh K. J., Ballouz R. L., Jutzi M., Hanus J., Michel P.

Speaker affiliation: Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France

Title: Formation of Large Multi-asteroid Systems through Sub-catastrophic Impacts

Abstract

Large main belt asteroids with diameters greater than approximately 100 km are thought to be remnant planetesimals. Catastrophic disruptions of such large asteroids leads to the formation of asteroid families, which provide clues on collisional processes at large scales and on the collisional evolution of the asteroid belt. A subset of these large asteroids also have one or more satellites, which are also thought to form by collisions. The main constraints we consider for large multi-asteroid systems are: (i) primaries have rotation periods 5-6 h, which is significantly more rapid than the 10 h spin period of the average large main belt asteroid, (ii) primaries are more elongated than average as indicated by light curve amplitudes and direct imaging, (iii) multi-asteroid systems are predominantly C-complex systems, with no known S-complex multi-asteroid system. Previous numerical studies on satellite formation by collisions do not track shape and spin of the primary or the long term dynamical evolution of satellites and are therefore unable to explain the demographics of large multi-asteroid systems. Here, we use a smoothed particle hydrodynamics code to model the initial impact and shock propagation of a satellite-forming impact followed by an N-body code to model the gravitational accumulation phase to determine the shape and spin of the primary as well as the orbits of any bound ejecta. Finally, we follow the long term dynamical and collisional evolution of the ejecta until they become stable satellites. The results of our simulations explain why, for large asteroids, we only observe satellites around fast rotating, elongated, and low density (i.e., primitive types) primaries in the main belt.

Author: *Almeida A.*

Speaker affiliation: Faculdade de Ciências da Universidade do Porto

Title: Tangential Velocity constraint for orbital maneuvers with Theory of Functional Connections

Abstract

Maneuvering a spacecraft in the cislunar space is a complex problem, since it is highly perturbed by the gravitational influence of both the Earth and the Moon, and possibly also the Sun. Trajectories minimizing the needed fuel are generally preferred in order to decrease the mass of the payload. A classical method to constrain maneuvers is mathematically modeling them using the Two Point Boundary Value Problem (TPBVP), defining spacecraft positions at the start and end of the trajectory. Solutions to this problem can then be obtained with optimization techniques like the nonlinear least squares conjugated with the Theory of Functional Connections (TFC) to embed the constraints, which recently became an effective method for deducing orbit transfers. In this paper, we propose a tangential velocity (TV) type of constraints to design orbital maneuvers. We show that the technique presented in this paper can be used to transfer a spacecraft (e.g. from the Earth to the Moon) and perform gravity assist maneuvers (e.g. a swing-by with the Moon). In comparison with the TPBVP, solving the TV constraints via TFC offers several advantages, leading to a significant reduction in computational time. Hence, it proves to be an efficient technique to design these maneuvers.

Authors: *Alnajjarine A.*, Laskar J., Mogavero F.

Speaker affiliation: Observatoire de Paris, France

Title: Resonant Dynamics Across Planetary Systems: A Numerical Averaging Approach

Abstract

Extrasolar systems commonly exhibit planets on eccentric and inclined orbits, many of which are close to or in mean-motion resonances (MMRs), showcasing the diversity of exoplanetary system architectures. To effectively address this diversity, we have developed numerical models that average the resonant Hamiltonian numerically to investigate the secular orbital dynamics within three-body systems. Our approach begins with the development of first-order numerical averaging methods, based on Schubart's averaging scheme (1964) introduced for asteroidal MMRs. By using Hamiltonian perturbation theory, we further extend our numerical averaging approach to second-order in planetary masses, enhancing the precision of our models and thereby enabling more accurate representations of orbital evolutions. We validate our methods against well-known planetary configurations, such as the Jupiter-Saturn system, as well as exoplanetary systems like WASP-148, demonstrating the applicability of our models across a wide range of resonant configurations.

Authors: Minglibayev M., Prokopenya A., *Assan B.*, Kosherbayeva A.

Speaker affiliation: Al-Farabi Kazakh National University

Title: Investigation of the many body-problem with variable masses by methods of perturbation theory

Abstract

We investigate the classical problem of many bodies with variable masses attracting each other according to Newton's law of universal gravitation. In the framework of the considered model, the masses of all bodies may change isotropically at different rates and the reactive forces do not arise. So applying Newton's second law, one can easily write the equations of motion of the bodies which look similar to the case of constant masses. The laws of the masses change are arbitrary twice differentiable given functions of time and dissipation of the mass and energy of the system takes place. The equations of motion are not integrable and we apply the canonical perturbation theory to their investigation using an aperiodic motion along quasi-conical section as the unperturbed one [1,2]. As an example, we consider the Sun-Jupiter-Saturn-Uranus-Neptune system and simulate its future dynamical evolution. In this case, the Sun will erupt as a red supergiant and there will be a strong increase in size and rapid loss of mass of the Sun [3]. Two-stage calculations are performed in the interval of (800 + 5) million years. Although the Sun will lose half of its mass, our calculations show that the system, Sun + outer planets, will "survive".

References

[1] Minglibayev, M. Zh.: Dinamika Gravitiruyushchikh Tel S Peremennymi Massami i Razmerami (Dynamics of gravitating bodies with variable masses and sizes) . LAP LAMBERT Academic Publishing, Germany (2012).

[2] Prokopenya, A. N., Minglibayev, M. Z., Kosherbayeva, A. B.: Derivation of evolutionary equations in the many-body problem with isotropically varying masses using computer algebra. Programming and Computer Software 48, 107–115 (2022)

[3] Veras, D.: The fates of solar system analogues with one additional distant planet. MNRAS 463(3), 2958–2971 (2016)

Authors: *Balossi R.*, Tanga P., Sergeyev A., Cellino A., Spoto F.

Speaker affiliation: Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France

Title: Identifying asteroid families from Gaia DR3 spectra

Abstract

The Gaia Data Release 3 (DR3) contains reflectance spectra for 60518 asteroids over the range 374 nm - 1034 nm, representing a huge sample compared to previous surveys available in the literature. We developed a procedure to identify asteroid families using only the spectra reported in the DR3. Our method is based (1) on a color taxonomy specifically built on Gaia data and (2) the similarity of spectra of candidate members with respect to a template spectrum of a specific family. We tested our procedure on two L- types families, Tirela/Klumpkea and Watsonia, which are known for their connection to Barbarian asteroids, potentially abundant in Calcium-Aluminum Rich Inclusions. We were thus able to identify objects in the halo of Tirela/Klumpkea and possible interlopers. We also find an independent group of eight asteroids erroneously linked to the family by the HCM. As a consequence, the knowledge of the size distribution is much improved with a more consistent shape at the larger end. The Watsonia family turned out to be a more intricate case, mainly due to its smaller size and the less marked difference between the spectral types of the background and of the family members. However, the spectral selection helped to identify objects that were not seen by the HCM, including a cluster separated from the family core by a resonance. For both families, the V-shape is thus better defined, leading to a revised age estimation based on spectra alone. Our work proves the advantage of combining the classical HCM approach to spectral properties obtained by Gaia, for the study of asteroid families. Future data releases will further expand the capabilities of this method.

Authors: *Benet L.*, Ramírez Montoya L. E., Pérez-Hernández J. A.

Speaker affiliation: Universidad Nacional Autónoma de México

Title: Jet transport for the orbit determination problem

Abstract

I will present recent advances in the orbit determination problem exploiting Jet Transport techniques. Jet transport allows to consider small deviations around a given initial condition (or parameters) of an initial value problem as truncated polynomials in those variables, exploiting automatic differentiation techniques. We illustrate its application by extending Gauss method, and also considering short arcs. Its advantages and current limitations will be discussed.

Author: *Bernardi F.*

Speaker affiliation: Space Dynamics Services srl

Title: Milani as a "business man": his legacy at SpaceDyS

Abstract

Andrea Milani and his team decided in 2011 to start a new spin-off company named Space Dynamics Services srl - SpaceDyS. This company has now 13 years and it does business in the space sector, in particular in space dynamics involving natural objects, such as asteroids, but also artificial objects such as space debris, satellites, space missions. This talk will present an overview of Milani's legacy as a business man, and his important contribution and strategic view on consolidating the success of the company.

Author: *Bianco G.*

Speaker affiliation: Agenzia Spaziale Italiana, Centro di Geodesia Spaziale

Title: Space Geodesy in Italy

Abstract

The Space Geodesy Centre of the Italian Space Agency is one of the few core stations of the GGOS (Global Geodetic Oberving System) ground network. A "core station" hosts all the three main space geodetic techniques, namely Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS), precisely co-located in a common area.
The GGOS mission is the maintenance and the improvement of the International Terrestrial Reference Frame (ITRF) and its connection with the International Celestial Reference Frame (ICRF): each observing technique has its strengths and weaknesses with respect to the so-called three pillars of geodesy, namely geokinematics, earth gravity field and earth rotation. Satellite Laser Ranging is particularly efficient in measuring the low-order coefficients of the geopotential and the instantaneous position of the Earth Center of Mass, which is the origin of the Terrestrial Reference Frame.

Author: *Bottke W.*

Speaker affiliation: Southwest Research Institute

Title: Collisional Evolution and Early Bombardment in the Outer Solar System

Abstract

One of the earliest attempts to model the collisional evolution of the primordial Kuiper belt (PKB) came from Davis and Farinella (1997). Their work was ambitious, in that it came only five years after the first Kuiper belt object was discovered (after Pluto and Charon). In this talk, we continue their legacy, but with the benefit of 27 years of additional knowledge and constraints. In our work, we also consider the tumultuous early era of outer solar system evolution, which culminated when Neptune migrated across the PKB and triggered a dynamical instability among the giant planets. This event led to the ejection of $\sim 99.9\%$ of the PKB (here called the destabilized population), heavy bombardment of the giant planet satellites, and the capture of Jupiter's Trojans. Using the collisional evolution code Boulder, we modeled what happened to all three populations. Our constraints included the size-frequency distributions (SFDs) of the Trojan asteroids and craters on the giant planet satellites. Using this combination, we solved for the unknown disruption law affecting bodies in these populations. The weakest ones, from an impact energy per mass perspective, were diameter $D \sim 20$ m. Overall, collisional evolution produces a power-law-like shape for multikilometer Trojans and a wavy-shaped SFD in the PKB and destabilized populations. The latter can explain (i) the shapes of the ancient and younger crater SFDs observed on the giant planet satellites, (ii) the shapes of the Jupiter family and long-period comet SFDs, which experienced different degrees of collision evolution, and (iii) the present-day impact frequency of superbolides on Jupiter and smaller projectiles on Saturn's rings. Our model results also indicate that many observed comets, most which are $D < 10$ km, are likely to be gravitational aggregates formed by large-scale collision events.

Our results can also be used to examine the bombardment history of the giant planet satellites. We find all of them are missing their earliest crater histories, with the likely source being impact resetting events. Iapetus, Hyperion, Phoebe, and Oberon have surface ages that are a few Myr to a few tens of Myr younger than when Neptune entered the PKB (i.e., they are $4.52 - 4.53$ Gyr old). The remaining mid-sized satellites of Saturn and Uranus, as well as the small satellites located between Saturn's rings and Dione, have surfaces that are younger still by many tens to many hundreds of Myr ($4.1 - 4.5$ Gyr old). A much wider range of surface ages are found for the large moons Callisto, Ganymede, Titan, and Europa (4.1, 3.4, 1.8, and 0.18 Gyr old, respectively). At present, we favor the idea the mid-sized and larger moons formed within protoplanetary disks, which provide the best match to their crater histories.

Author: *Bougakov A.*

Speaker affiliation: IMCCE, Paris

Title: The isochrone symplectic integrator for galactic dynamics

Abstract

The most distant trans-Neptunian objects feel the gravitational pull of the galactic environment outside the Solar system: passing stars and galactic tides. In order to quantify the evolution of these forces since the formation of the Solar system, we need to study the statistics of possible trajectories of the Sun in the Milky way, which requires an effective symplectic integrator. I will present the construction of a symplectic scheme based on Hénon's isochrone potential.

Author: *Căliman A.*, Daquin J., Libert A.-S.

Speaker affiliation: University of Namur

Title: Chaos detection using Lagrangian Descriptors and Differential Algebra. Application to extrasolar systems

Abstract

Over the years, several numerical tools have been designed to discriminate chaotic from regular trajectories in dynamical systems. Recently, a sharp and sensitive non-variational chaos indicator based on the second-derivatives of the arc-length Lagrangian Descriptors (LDs), hereafter denoted as FD-LD, has been developed. The indicator, valid for both discrete and continuous systems, involves approximations of discrete like Laplacians obtained by finite difference (FD) methods which are sensitive to noise and prone to numerical errors. In this contribution, we introduce a new framework, denoted DA-LD, which exploits the Differential Algebra (DA), used as a form of automatic differentiation, in order to estimate the required derivatives of the LD metric up to machine precision. For the 2-dimensional standard map, along with higher dimensional versions, we show the significant improvement of DA-LD in the accuracy of discriminating ordered or chaotic trajectories, in particular in recovering the nature of orbits in the vicinity of thin dynamical structures such as resonant chains or junctions. We further demonstrate the benefits of the DA-LD framework by studying the stability of extrasolar three-planet systems for which sparsely and non-uniformly sampled initial conditions are considered.

Author: *Campo Bagatin A.*

Speaker affiliation: Universidad de Alicante

Title: Where do asteroid binaries form? Comparing Didymos and Dinkinesh collisional evolution

Abstract

On the 26th of September, 2022, the near-Earth asteroid (NEA) binary system Didymos was visited by the DART (NASA) spacecraft and the LICIACube (ASI) cubesat [1, 2]. DART impacted Dimorphos, the secondary of the system, in the first-ever asteroid deflection experiment [3], while LICIACube flew by the system right after the impact [4]. One year later, on the 4th of November, 2023, the Lucy (NASA) spacecraft -on its way to the Jupiter Trojan asteroid region- flew by the inner asteroid belt binary system Dinkinesh. The two systems share some similar characteristics -they both belong to the S taxonomic classification- but they also exhibit some differences. The two primary bodies have essentially the same size ($\sim$800 m), Dinkinesh has a clear top-shape, while Didymos looks like a degraded one [5, 6]. It is interesting that none of the satellites had the expected prolate shape for an asteroid satellite. In fact, Dimorphos was inferred to have an oblate shape [7], while the Dinkinesh satellite images reveal what it seems to be a contact binary satellite. The Didymos primary is spinning very fast, at 2.26 hr, on the edge of instability [8], and the orbital period of Dimorphos was 11.92 hr. Instead, the spin period of Dinkinesh is still not clear. An unambiguous former period of 52.67 ± 0.04 hr [8] was measured for the system (previous to the satellite discovery), and may now be revisited to disentangle the primary rotation and the satellite orbital motion. Didymos is a NEA with an eccentric orbit, driving it well inside the inner asteroid belt, where it spends 1/3 of its orbital period, while Dinkinesh is an inner belter spending less than 30% of its orbit inside the limits of the asteroid belt ($q < 2.06$ au). On the other hand, Dinkinesh is not far away from a secular resonance that may dive it into the NEA region in the future. We recently studied the collisional history of the Didymos system in the frame of the interpretation of the surface features observed by the DART spacecraft, which may be relevant to the operations of the Hera (ESA) [9] space mission that will thoroughly study the system in 2026/27. We now do the same exercise on Dinkinesh, and compare collisional probabilities and distributions of impact velocities, and we will try interpretations of the evolution of the two systems. Is Dinkinesh an early version of Didymos? Is it possible to relate orbital evolution of inner belt asteroids to their future evolution as NEAs? Is there a common formation pattern in the asteroid belt for km-size binary asteroids with top-shape-like primaries? Are collisional processes in the asteroid belt driving the formation of binary systems, as opposed to constant gentle spin up by YORP, eventually triggering fission or mass shedding? With this study we try to contribute to the debate and find common processes that may have led Didymos and Dinkinesh to look like they currently are.

References

[1] Rivkin A. S. et al. (2021) PSJ, 2, 173. [2] Dotto E. et al. (2021) PSS, 199, 105185. [3] Cheng A. F. et al. (2023) Nature, 616, 457-460. [4] Dotto E. et al. .(2024) Nature. 627, 505-509. [5] Barnouin O. S. (2024) Nature Comm. In press. [6] Campo B. et al. (2024) Nature Comm. In press. [7] Daly R. T. et al. (2023) Nature, 616, 443-447. [8] Trògolo et al. (2023) Icarus, 397, 115521. [9] Mottola S. et al. (2023) MNRAS Letters, 524, L1-L4.

Author: *Carbognani A.*

Speaker affiliation: Italian National Institute for Astrophysics (INAF)

Title: Detection of a rotation period increase for the Peregrine-Centaur booster

Abstract

On January 8, 2024, Astrobotic's Peregrine Mission One was launched. From 9 to 18 January, we made photometric observations of the second stage of the Peregrine's rocket, detecting an exponential increase in the rotation period, from 3 to approximately 22 minutes. This increase in the rotation period is not due to a loss of residual gas from one end of the rocket but to magnetic braking caused by the tail of the Earth's magnetosphere.

Author: *Celletti A.*

Speaker affiliation: Università di Roma Tor Vergata

Title: The synergy between classical perturbative methods and machine learning techniques in Celestial Mechanics

Abstract

Classical perturbation theory is a cornerstone of Celestial Mechanics and Astrodynamics for the study of the dynamics of nearly-integrable Hamiltonian systems. Further developments are represented by KAM theory and Nekhoroshev's theorem. All these mathematical theories have been successfully applied to study the stability of models of Celestial Mechanics. In some cases, they can even be extended to dissipative systems, most notably the so-called conformally symplectic systems, which enjoy important geometric properties.
As a complement of the analytical results, machine learning methods can be used to get information on the dynamics. These techniques have been used to classify regular and chaotic motions in satellite's rotational dynamics and to cluster space debris after a break-up event. The overall results have the potential to pave the way to a synergetic use of perturbative and machine learning methods.

Author: *Chesley S.R.*

Speaker affiliation: JPL-NASA

Title: Orbital and physical changes to asteroid Dimorphos caused by the DART impact

Abstract

NASA's Double Asteroid Redirection Test (DART) mission impacted Dimorphos, the satellite of binary near-Earth asteroid (65803) Didymos, in September 2022. In collaboration with the mission investigation team and numerous ground-based observers, we have estimated the changes in the orbital and physical properties of the system due to the impact. Our primary observations were ground-based photometry, which revealed the timing of mutual eclipses and occultations between the binary system components. We also fit radar measurements and DART camera observations. We estimate that the DART impact instantaneously changed the along-track velocity of Dimorphos by -2.63 ± 0.06 mm/s, leading to a reduction in Dimorphos's orbital period of 32.7 minutes ± 16 s , leading to a post-impact period of 11.377 ± 0.004 h. We also find that over the subsequent several weeks the orbital period decayed by an additional 34 ± 15 s, presumably due to continuing loss of angular momentum from escaping ejecta. The post-impact orbit exhibits apsidal precession, with a rate estimated to a precision of 3%. Under our model, apsidal precession is driven by the Didymos oblateness (J_2), as well as the spherical harmonics coefficients, C_{20} and C_{22}, of Dimorphos's gravity. Under the assumption that Dimorphos is a triaxial ellipsoid with a uniform density, its C_{20} and C_{22} estimates imply axial ratios, a/b and a/c, of about 1.3 and 1.6 respectively. Pre-impact images from DART indicate Dimorphos's shape was close to that of an oblate spheroid, and thus our results indicate that the DART impact significantly altered the shape of Dimorphos.

Author: *Chiofalo M.*

Speaker affiliation: University of Pisa, INFN-Pisa

Title: Quantum Technologies for Fundamental Physics, Cosmology and Astrophysics

Abstract

The accuracy and control achieved in the engineering of quantum matter is opening up unprecedented perspectives to investigate open problems in fundamental physics, cosmology and astrophysics, with the design of table-top up to very-long baseline terrestrial atom interferometers. I will discuss the main underlying concepts and provide a gallery of current efforts in this fascinating interdisciplinary science, which I have undertaken after my encounter with Paolo, Andrea, and Anna.

Author: *Cicalò S.*

Speaker affiliation: Space Dynamics Services srl

Title: Low-Thrust transfer to a large Sun-Earth DRO through a SEL point launch from the Cubesat HENON Mission Analysis

Abstract

The HEliospheric pioNeer for sOlar and interplanetary threats defeNce (HENON) mission is a 12U-CubeSat Space Weather mission, designed to operate in a Sun-Earth Distant Retrograde Orbit (DRO) at more than 12 million km from the Earth. HENON will embark payloads tailored for Space Weather (SWE) observations, and a high-resolution energetic particle radiation monitor, making it the first mission ever providing a real time monitoring of the particle radiation environment in the deep space. The mission phases A/B have been conducted by a consortium led by Argotec, with INAF, University of Calabria, University of Florence and SpaceDyS, under ESA GSTP contract through the financial support of ASI. HENON has many important goals including the demonstration of CubeSat capabilities in deep space, and to pave the way for a future fleet of spacecraft on a DRO, to provide continuous near real-time measurements for SWE forecasting.

This presentation focuses on the Mission Analysis main challenges and results, in particular regarding the definition of the baseline transfer trajectory to the target DRO. The transfer is planned to be performed via a rideshare to SEL2, employing on-board electric propulsion only, from the vicinity of the Earth to deep space, which will be a pioneering experiment in itself. A brief overview of classic transfer strategies from Earth to DRO with impulsive maneuvers will be given. Then, under suitable assumptions on the electric propulsion system performances, SC mass and propellant budget, it will be shown that the HENON target DRO can be reached in about 1 year, exploiting the launch scenario of a typical SEL2 mission, and taking into account also periodic interruptions of thrusting to allow for TT&C. Preliminary results on navigation, contingency scenarios, and disposal will be also outlined, as work in progress of mission phase C.

Author: *Correia A.*

Speaker affiliation: University of Coimbra

Title: New techniques to study the tidal evolution of planetary systems

Abstract

We present new methods to model the tidal evolution of multi-body systems. We derive the equations of motion in a vectorial formalism, which is frame independent and valid for any rheological model. We compute the instantaneous deformation of extended bodies using a differential equation for the inertia tensor. This approach can take into account all kinds of perturbations, including chaotic motion. We present a new open-source N-body code to handle the tidal evolution of multi-body systems. We show that for rocky bodies, spin-orbit resonances arise naturally and can develop high obliquity states.

Author: *Courtot A.*

Speaker affiliation: IMCCE - Paris Observatory

Title: Chaos in Northern and Southern Taurids

Abstract

Meteor showers are visible when meteoroids ejected from a parent body (comet or asteroid) encounter the Earth and lit up in its atmosphere. Those very small bodies are influenced by both gravitational and non-gravitational forces (solar radiation pressure and Poynting-Robertson drag), which makes them interesting to study in terms of chaos.

In previous studies, we tackled three well-known meteor showers with widely different orbits, the Geminids (near-Earth orbit), the Draconids (Jupiter family comet-like orbit) and the Leonids (orbit like Halley-type comet) [Courtot et al., 2023, 2024]. We showed the influence of mean-motion resonances combined with close encounters on those streams. This talk, however, will focus on the Taurids (near-Earth orbit but distinct from Geminids). Contrary to the other showers studied, the parent body of this meteor shower is not clearly established, although its orbit might be close to the comet 2P-Encke [Egal et al., 2021, 2022]. The Taurids is formed of several currents of which only two are studied: the Northern and Southern Taurids. Both streams have similar orbits, but their argument of perigee and right ascension of ascending node are opposed. The specificities of the Taurids (several currents, origin unclear) makes it an interesting object to study in terms of chaos.

We drew chaos maps using the chaos indicator OFLI [Fouchard et al., 2002] over 1000 years and we obtained maps quite distinct from our previous studies. In this talk, I will present those maps and their characteristics, focusing on the effects of mean-motion resonances and close encounters with several planets, for different size bins.

Author: *Davis D.*

Speaker affiliation: Planetary Space Institute

Title: A memory of 20 years with Paolo

Abstract

I will be talking about my memories of many collaborations with Paolo starting in the early 1980s and continuing till 2000.

Authors: *Dermott S. F.*, Li D., Christou A. A.

Speaker affiliation: University of Florida

Title: Yarkovsky forces and the ages of main belt asteroids

Abstract

Two separate factors determine the strengths of the Yarkovsky forces experienced by asteroids. The first factor is the quantity of solar photons intercepted by an asteroid over one rotational cycle. It is this factor that largely determines the distribution of family asteroids in inverse diameter ($1/D$) and semimajor axis (a) space. The second factor depends on the asymmetric distribution of the photons re-radiated from a rotating asteroid. This phase factor is largely determined by the ratio, W of the surface thermal inertia to the square root of the asteroid rotational period. While the asteroids in a family may have a common thermal inertia, they do not have a common rotational period, suggesting that family asteroids should have a wide range of W and that the $1/D-a$ distribution should not be a simple V-shape. We discuss the factors that determine the distribution of family asteroids in $1/D - a$ space and show, using the example of the Hungaria asteroid family, how an analysis of the distributions of the semimajor axes and the rotational periods could be used to estimate the age of an asteroid family, the strengths of the Yarkovsky forces, and the lifetimes of small main belt asteroids.

Authors: *Di Ruzza S.*

Speaker affiliation: Università di Palermo

Title: Chaotic coexistence of librational and rotational dynamics in the averaged planar three-body problem

Abstract

We deal with the planar three body problem. Through an appropriate change of reference frame and rescaling of the variables and the parameters introduced, the Hamiltonian of the three-body problem is written as a perturbed Kepler problem. In this system, new Delaunay variables are defined and a suitable configuration of the phase space and the mass parameters is chosen. In such a system, wide regions of librational and rotational motions where orbits are regular and stable are found. Close to the separatrix of these regions, the existence of chaotic motions presenting a double rotational and librational dynamics is proved, numerically, through Poincaré sections and the use of FLI.

Authors: *Dogkas A.*

Speaker affiliation: University of Pisa

Title: An Analytical Method for Resonant Proper Elements

Abstract

Proper elements are quasi-integrals of the motion and have been used for the identification of asteroid families (see Knezevic (2015) for a historical review) and for the clusterization of space debris (Celletti, Pucacco, & Vartolomei (2022) and references therein). Naturally, the domain where these elements are conserved is restricted by resonances. In this case, synthetic, semi-analytical (Morbidelli (1993)) or purely numerical (Knezevic & Milani (2000)), proper elements, which use numerical methods to filter out the oscillations of the orbital elements, can be used to compute the resonant proper actions.

In this work, we introduce analytical methods for the computation of the resonant proper actions. By reconstructing the librational tori, we eliminate the librating angles obtaining quasi-integrals of the motion as functions of the initial conditions of the body. Furthermore, we give approximations for the degree to which the proper elements are conserved when approaching an isolated resonance.

Finally, we apply this method in the case of space debris under the influence of the Geopotential, the Moon, and the Sun, both for mean motion and secular resonances.

Authors: *Dvorak R.*, Cuntz M.

Speaker affiliation: Institute of Astrophysics, University of Vienna

Title: The Stability of Retrograde Orbits between Jupiter and Saturn

Abstract

Between the giant planets Jupiter and Saturn about 60 asteroids exist in orbits with relatively large eccentricities. Previously, based on numerical investigations, this domain was studied for asteroids with small eccentricities indicating many stable regions with large escape times of up to several hundred million years (paper 1). It has been found that especially bodies of large inclinations are orbitally stable, including massive planets (paper 2). However, a study of retrograde orbits has still been missing. Hence, we decided to investigate the stability behaviour for massless bodies from vertical moving bodies (i=90 deg) up to i=180 degrees. Previous studies based on simplified models (e.g., the restricted three body problem) indicate that retrograde orbits are much more stable than those with small inclinations. For the full N-body problem, a model for the Solar System, we show that starting at i=90 degrees the stability behaviour increases significantly leading to escape times of billions of years. Numerical results obtained through an efficient integrator for a real system underline that these kinds of orbits are highly relevant especially for extrasolar planetary systems.

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Dvorak, R., & Cuntz, M. 2023, Astron. Notes, 344 (paper 2)

Authors: *Faggioli L.*

Speaker affiliation: NEOCC at ESA/ESRIN

Title: Monitoring Near-Earth Asteroids: ESA NEOCC Risk Assessment pillar

Abstract

One of the main goals of the ESA NEO Coordination Centre (NEOCC) is to compute the orbits of near-Earth objects (NEOs) and assess their probability of impacting Earth. These activities are carried out by the Risk Assessment pillar, one of the three pillars of ESA's Planetary Defence Office.

To achieve this goal, the NEOCC operates Aegis, an automated orbit determination and impact monitoring system developed by SpaceDyS s.r.l. through industrial contracts from ESA. The most important services provided by the Aegis system include maintaining the orbital catalogue of near-Earth asteroids (NEAs) with their uncertainties, and the NEOCC Risk List, which is a set of NEAs that have a non-zero probability of colliding with Earth. Other services provided by Aegis include ephemerides computation, close approaches lists, and inputs for the NEO toolkit.

The Risk Assessment pillar also operates and develops the Meerkat software, an automated monitoring system for imminent impactors. Since its introduction at the Planetary Defense Conference 2021, Meerkat successfully detected the last four impactors (2022 EB5, 2022 WJ1, 2023 CX1, and 2024 BX1), and it has been improved in terms of stability, reliability, and performance. Since December 2022, a Meerkat mailing list is opened for subscription to the Planetary Defense community.

After an introduction of the Aegis and Meerkat systems, this presentation highlights some of the recent activities of the Risk Assessment Pillar carried out by operating these two software. These include: the development of an automated procedure for Yarkovsky effect detection on NEAs; the impact risk assessment of 2023 VD3 by considering time uncertainties; the negative observations exercise on 2010 RF12; the role of Meerkat during the impacts of 2022 WJ1, 2023 CX1, and 2024 BX1.

Author: *Farnocchia D.*

Speaker affiliation: Jet Propulsion Laboratory, California Institute of Technology

Title: The high-precision modeling of the trajectory of asteroid Bennu

Abstract

In his Brouwer Award presentation, Andrea Milani said that " *When the theories of motion for celestial bodies are constrained by observations they can provide the most quantitative and most accurate physical models.*" A prime example to back this claim is the estimation of the trajectory of near-Earth asteroid Bennu. Since its discovery in 1999, Bennu has been tracked by optical telescopes as well as radar during the close approaches to Earth in 1999, 2005, and 2011. Moreover, the OSIRIS-REx mission visited Bennu and provided extensive physical characterization and meter-level constraints on the position of the asteroid during nearly two years of proximity operations. This dataset required an unprecedented fidelity for the modeling of an asteroid's trajectory. In particular, special care is needed to take into account numerical errors, relativistic effects, and the contribution of hundreds of small-body perturbers. Radiation effects such as the Poynting–Robertson drag, so far only considered for interplanetary dust dynamics, now become a consideration for modeling the trajectory of a 500-m asteroid such as Bennu. Of special interest was the Yarkovsky effect, which is an important nongravitational acceleration in high-precision trajectory modeling as well as long-term dynamical evolution of asteroids. The Yarkovsky acceleration derived from thermophysical model based on the characterization of Bennu matches the observed deviations from the tracking data. As typical of near-Earth objects, encounters with Earth inject uncertainty in the future trajectory of Bennu. Thanks to the tracking data available, the trajectory of Bennu is deterministic through the Earth encounter in 2135. After the 2135 encounter, only statistical predictions are possible and there is a 0.06% probability of impact between 2178 and 2290.

Author: *Ferraz-Mello S.*

Speaker affiliation: Universidade de Sao Paulo

Title: Resonant asteroids and the architecture of the main belt

Abstract

The creative minds of Paolo Farinella and Andrea Milani often considered the architectural features of the main asteroidal belt, the Kirkwood gaps, the asteroid groups, the eccentricity excitation, and the scattering of asteroids associated with resonance crossings. In this communication, we review the present status of the investigations concerning these topics and the contributions of Paolo and Andrea to the present understanding of the asteroidal distribution and discuss the Alinda gap, the Hecuba gap and the Hilda group.

Author: *Fenucci M.*

Speaker affiliation: ESA PDO/NEOCC - Elecnor Deimos

Title: Countdown to impact: ESA NEO Coordination Centre response to asteroid 2024 BX1

Abstract

On 20 January 2024, asteroid 2024 BX1 impacted the Earth about 50 km west of Berlin. The object was discovered by Krisztián Sárneczky from the Piszkéstető Observatory few hours before impact, and the first set of observations was received by the Minor Planet Center in less than 30 minutes after the discovery. The object was immediatly inserted in the NEO Confirmation Page, with the temporary designation Sar2736.

In this talk we present the actions taken by the ESA NEO Coordination Centre (NEOCC) and the computations performed upon and right after the impact event. Operations began when the ESA Meerkat imminent impactor system notified an impact probability of 1 for Sar2736, that was computed with 7 observations only. Alerts were sent through the Meerkat mailing list and to the team of astronomers of the NEOCC, who promptly followed-up the object from Tenerife. Live computations of the impact corridor were performed simultaneously by the ESA Aegis system, showing significant improvements of the uncertainties as new astrometry became available. At 00:25 UTC of 21 January, the asteroid entered the Earth atmosphere and impacted at the predicted location and time. The entry point in the atmosphere was later used to predict the strewn field, that was compatible with the location of found meteorites. Finally, we show preliminary results of long-term dynamical simulations of 2024 BX1.

Author: *Fuentes-Munoz O.*

Speaker affiliation: Jet Propulsion Laboratory, California Institute of Technology

Title: Asteroid Orbit Determination in the Era of High-Precision Astrometry

Abstract

In recent years an increasing amount of high-precision astrometry has been made available to the community, allowing improved orbit determination of asteroids in the Solar System. Examples of remarkable contributions to this effort are the astrometric measurements of ESA's Gaia mission or stellar occultations.

In this talk we present the results of our recent paper, where we process the Gaia Focused Product Release (FPR) including observations of more than 156000 asteroids. The high precision of these astrometric observations requires careful modeling in the dynamics and observation models. We find that the offset of the center-of-light with phase angle is significant in the larger objects. Therefore, we improve the orbital fit with a correction of the location of the center-of-light. In addition, we inflate the uncertainty of the measurements to account for the unknown location of the center-of-mass relative to the center-of-light and unmodelled parameters of the center-of-light location.

In some cases, asteroids can encounter small-body perturbers during their Gaia FPR observational arc. With a Monte Carlo experiment we show that the uncertainties in the masses of these perturbers can cause differences in the orbits at the level of the formal uncertainties of very constrained orbits.

We show the effects of the observational and dynamical models in multiple examples as well as applications of the high-precision astrometric measurements, including updated impact probability analyses.

This research was supported by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Oak Ridge Associated Universities under contract with NASA.

Authors: *Giralt M.*, Alessi E.M., Guardia M., Baldomá I.

Speaker affiliation: Paris Observatory

Title: On the Arnold diffusion mechanism in Medium Earth Orbit

Abstract

Motivated by the need of preserving the operational orbital regions around the Earth, natural perturbations can be exploited to lead the satellites towards an atmospheric reentry at the end of life. In this way, it is possible to dilute the collision probability in the long term and reduce the disposal cost, also if departing from high-altitude regions. In the case of the Medium Earth Orbit (MEO) region, home of the navigation satellites (like GPS and Galileo), the main driver is the third-body perturbation. In this work, we show how an Arnold diffusion mechanism can trigger the eccentricity growth in MEO, so that the pericenter altitude drops into the atmospheric drag domain. Focusing on the case of Galileo, we consider a hierarchy of Hamiltonian models, assuming that the main perturbations on the motion of the spacecraft are the oblateness of the Earth and the gravitational attraction of the Moon. First, the Moon is assumed to lay on the ecliptic plane and periodic orbits and associated stable and unstable invariant manifolds are computed for various energy levels, in the neighborhood of a given resonance. Along each invariant manifold, the eccentricity increases naturally, achieving its maximum at the first intersection between them. This growth is, however, not sufficient to achieve reentry. By moving to a more realistic model, where the inclination of the Moon is taken into account, the problem becomes non-autonomous and the satellite is able to move along different energy levels. Under the ansatz of transversality of the stable and unstable manifolds in the autonomous case, checked numerically, Poincaré-Melnikov techniques are applied to show how the Arnold diffusion can be attained, by constructing a sequence of homoclinic orbits that connect invariant tori at different energy levels on the normally hyperbolic invariant manifold.

Author: *Gomes S.*

Speaker affiliation: Centre for Physics of the University of Coimbra

Title: The recent past dynamical evolution of the Uranian major satellites

Abstract

We have studied the recent past tidal and spin evolution of the Uranus satellite system. We have determined new constraints on the quality factors of Uranus and the satellites. We find that the system most likely encountered the 5/3 mean motion resonance between Ariel and Umbriel in the past, at about (0.7 ± 0.2) Gyr ago. Furthermore, we constrain the eccentricities and inclinations that the major satellites of Uranus should have just before the crossing of the 5/3 resonance, and show that the initial eccentricity of Ariel plays a key role to evade capture in this resonance. Finally, we successfully replicate the orbital and spin evolution of the five largest satellites during the resonance passage and track their evolution up to the present day.

Author: *Granvik M.*

Speaker affiliation: U Helsinki, Finland / Luleå U Tech, Sweden

Title: Constraining the characteristics of asteroid interiors with telescopic surveys

Abstract

The interiors of asteroids, that is, their bulk composition and structure, are largely unknown today except for a few special cases. Apart from drilling and radar sounding, both of which are techniques yet to be applied to asteroids, let alone applied to a large number of asteroids, our knowledge of asteroid interiors is based on indirect observations such as rotation rates as well as the compositions of members of asteroid families. In recent years, two destruction mechanisms have been shown to have non-negligible effect on the population of near-Earth asteroids (NEAs). First, asteroids are not falling all the way into the Sun (Farinella et al. 1994) but instead they are destroyed on orbits that bring them relatively close to the Sun (Granvik et al. 2016). The primary mechanism causing the destruction is still to be firmly determined, but the leading hypothesis at the moment is that solar irradiation is the main contributing factor, and an asteroid's composition affects the distance at which it is destroyed. Second, tidal disruptions during close and slow encounters with terrestrial planets have been proposed to affect NEAs, but the importance of tidal disruptions on the population level was discovered only recently (Granvik & Walsh 2024). Whereas the susceptibility to a destruction close to the Sun is likely to be primarily determined by an asteroid's bulk composition, the susceptibility for tidal disruption is likely to be primarily determined by interior structure of the asteroid. The major benefit compared to all other destruction mechanisms affecting NEAs, apart from collisions with planets, is that the rate of close encounters with both the Sun and the planets can be readily estimated through dynamical simulations. We can thus carry out simulations to predict the rate of asteroid destruction close to the Sun and planets as a function of bulk composition and structure. The resulting effects on the NEA population, in practice changes in orbit and size distributions, can then be compared with observations by telescopic surveys. The approach allows for testing different models of asteroid interiors by comparing to observational data obtained by telescopic surveys. I will summarize current and future efforts to understand the details of the destruction mechanisms and to utilize them for constraining the interior characteristics of asteroids including observational surveys, population models, laboratory experiments, and space missions.

Authors: *Grassi C.*, Gronchi G. F.

Speaker affiliation: University of Pisa

Title: Recent improvements to IOD methods

Abstract

Accurate initial orbit determination (IOD) methods are necessary to ensure convergence of iterative procedures that are commonly used to refine orbits once a higher number of observations becomes available. A category of IOD methods is based on the conservation of the Keplerian integrals (KI) in the 2-body problem. We will present different improvements to the KI methods, depending on the type of object we are considering. When the 2-body assumption is reliable, we propose the application of 2-body differential corrections to improve the preliminary orbit computed with the KI methods. On the other hand, especially for LEO orbits, the 2-body assumption for satellites of the Earth breaks down and the KI integrals are no longer conserved. In this case, we apply an iterative procedure that allows to include the effect of the J_2 term while using the KI methods. Results of numerical tests will be presented.

Author: *Gronchi G. F.*

Speaker affiliation: University of Pisa

Title: Keplerian integrals for preliminary orbit determination

Abstract

In the last 15 years different IOD methods have been developed at the University of Pisa, based on the conservation laws of Kepler's dynamics. Some of them have been successfully applied to the computation of orbits of asteroids and Earth satellites. We shall review these methods, including the most recent one, and describe some results.

Author: *Guzzo M.*

Speaker affiliation: Università di Padova

Title: Parametric approximations of fast close encounters of the planar three-body problem as arcs of a focus-focus dynamics

Abstract

A gravitational close encounter of a small body with a planet may produce a substantial change of its orbital parameters which can be studied using the circular restricted three-body problem. In this paper we provide parametric representations of the fast close encounters with the secondary body of the planar CRTBP as arcs of non-linear focus-focus dynamics. The result is the consequence of a remarkable factorization of the Birkhoff normal forms of the Hamiltonian of the problem represented with the Levi-Civita regularization.

Author: *Heissel G.*

Speaker affiliation: European Space Agency/ESTEC and Paris Observatory/LESIA and VLTI/GRAVITY Collaboration

Title: Relativistic orbit models for the Galactic Centre: The S-stars as Dark Matter and Spin probes

Abstract

Infrared observations of the galactic centre revealed a cluster of young bright stars on elliptical orbits around a common focal point – the S-star cluster. The determination of their orbits allowed a precise measurement of the mass of the central body – 4.3 million solar masses. These and other observations leave little doubt about that this central body is a massive black hole. Observations of the star S2, on an eccentric 16 year orbit, further allowed direct observations of two general relativistic effects: the gravitational redshift and the Schwarzschild advance of the argument of pericentre.

After summarising the state of the art of S-star orbit models I will discuss two major science cases currently under investigation: (1) the measurement of the black hole spin via an observation of the Lense-Thirring precession of the orbit of S2; (2) the constraining of dark matter models via the observation of the imprints it leaves as a perturbation in the orbit of S2.

If time is left, I would also like to draw attention to a circumstance often overlooked in relativistic orbit modelling: an orbital parametrisation in terms of osculating orbital elements is unique if and only if it is associated with a coordinate system.

Author: *Kanamaru M.*

Speaker affiliation: University of Tokyo

Title: Numerical Verification of Yarkovsky Effect on Binary Asteroid

Abstract

Following the successful impact experiment of the DART spacecraft on Dimorphos, the satellite of a binary asteroid Didymos, the European spacecraft mission Hera plans a rendezvous and detailed observations. Japan provides the thermal infrared imager (TIRI) onboard Hera. We have been developing thermophysical simulations to estimate thermophysical properties from thermal images of the asteroids and to predict their dynamical evolution due to perturbations by thermal radiation (non-gravitational effects).

We conducted a thermophysical modeling of a binary asteroid to understand its equilibrium state and dynamical lifetime. We calculated the Yarkovsky-Schach effect by simulating the temperature distribution of the satellite, considering an eclipse by the primary component's shadow. The Yarkovsky-Schach effect, which has been studied as a mechanism of orbital evolution of Saturn's ring particles, is a perturbation on a component that enters the shadow of the main planet. It was found that the Yarkovsky-Schach effect causes the orbital evolution of the satellite towards a synchronous orbit where the orbital and rotational periods are equal.

Author: *Knežević Z.*

Speaker affiliation: Serbian Academy of Sciences

Title: Proper elements for resonant asteroids

Abstract

There are two basic ways to compute parameters which have the property of being "proper", that is quasi constant in time, for asteroids located in or near the secular resonances. One is the semianalytic method by Morbidelli (1993), while the other, the synthetic method, is a purely numerical procedure based on double filtering of time series of asteroid osculating elements, proposed by Milani et al. (2017). The latter was one of the last contributions to the field by Andrea Milani. Both methods are briefly described and compared, while some clarifications and recent upgrades of the synthetic method are described in more detail. The results of computation of resonant proper elements for a couple of nonlinear secular resonances are shown and discussed in terms of the accuracy of obtained proper values.

Authors: *Kosherbayeva A. B.*, Prokopenya A. N., Minglibayev M. Z., Chichurin A. V.

Speaker affiliation: Al-Farabi Kazakh National University

Title: Secular evolution of the non-stationary seven-planet system Trappist-1

Abstract

The Solar System is a multi-planetary system. Due to the discovery of exoplanetary systems, investigation of multi-planetary systems is a topical problem. The study of the dynamical evolution of multi-planetary extrasolar systems gives an opportunity to look at the evolution of the Solar System from different points of view. In the present work, we study the seven-planet extrasolar system Trappist-1 [1], assuming the masses of the parent star and planets to be variable [2]. The problem is studied in the framework of the seven-planet eight-body problem with masses varying isotropically at different rates.

The problem is not integrable and so the methods of perturbation theory developed for non-stationary multi-planet systems are applied for its study [3,4]. A linear non-autonomous system of differential equations of perturbed motion is given in explicit form. Differential equations describing the secular perturbations of the orbital elements are written in terms of the osculating analogs of Poincaré variables and consist of twenty-eight first order equations [5]. The coefficients of these equations depend on time in a complex way and so finding their analytical solution is not possible. We assume that the masses of bodies vary isotropically with different rates according to the Eddington-Jeans law.

We studied the resulting system of equations for secular perturbations by numerical methods for the time interval corresponding to one million revolutions of the first planet, for different laws of mass variation. Comparisons are made with the corresponding constant-mass problem, and the effects of mass variability on the dynamical evolution of orbital elements under different laws of mass variations are analyzed.

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Authors: *Lasagni Manghi R.*, Carletti L., Mochi M., Paoli R., Gramigna E., Zannoni M., Lari G., Tortora P., Tommei G.

Speaker affiliation: University of Bologna

Title: Didymos ephemeris reconstruction using astrometric data and radiometric data from the Hera mission

Abstract

Context: The planetary defense efforts reached a significant milestone with the success of NASA's Double Asteroid Redirection Test (DART) mission. The mission effectively demonstrated the kinetic impactor technique as a viable means for asteroid deflection by impacting the DART spacecraft on Dimorphos, the minor component of the Didymos binary asteroid system. Although the impact's effects on the mutual orbit of the asteroids have been measured, its effect on the system heliocentric orbit, described by the momentum enhancement parameter $\beta_{\odot}$, is yet to be determined. Scheduled for launch in October 2024, ESA's Hera mission aims to investigate the Didymos system in the aftermath of the DART impact.

Aim: In this work, we present a reconstruction of the heliocentric trajectory of the binary asteroid system Didymos. Through an orbit determination process, we assess the accuracy of its reconstructed ephemeris and explore the observability of $\beta_{\odot}$ and other critical parameters related to its non-gravitational motion.

Methods: To reach these goals, we first performed an orbit determination process using currently available astrometric observations. Then, we conducted a covariance analysis, adding simulated measurements from future ground-based observations and radiometric measurements collected by the Hera mission, namely range and ΔDOR. Specifically, we assessed how the accuracy of the solved-for parameters is influenced by the frequency and nature of the various observations collected throughout the Hera mission. Furthermore, we performed a sensitivity analysis using different formulations of the Yarkoswki effect, with increasing levels of complexity, within the orbit determination filter.

Results: We find that current measurements are insufficient to estimate $\beta_{\odot}$. However, introducing range and ΔDOR observations collected by Hera substantially increases the signal-to-noise ratio of the estimated parameters and significantly reduces the position uncertainties over the whole estimation arc. Finally, we show that accurate modeling of the Yarkowsky effect is crucial for accurately estimating $\beta_{\odot}$ and separating its impact from the asteroid's non-gravitational motion.

Author: *Laskar J.*

Speaker affiliation: IMCCE

Title: Controversial issues in the Earth-Moon evolution

Abstract

Due to tidal interaction between the Earth and the Moon, dissipation occurs, slowing Earth's rotation while causing the Moon to move away from the Earth at a present rate of 3.8 cm per year. Laser reflectors left by Apollo astronauts on the Moon's surface enable extremely precise measurements of this recession. Meanwhile, rock samples brought back from the same Apollo missions helped estimate the Moon's age at 4.25 Ga. Until recently, no physical model could account for Moon's history from its formation near the Earth to its present position. This gap was filled by a scenario fitting both the age of the Moon and its measured present recession (Farhat et al., 2022). Despite agreement with geological evidence, alternate propositions arose last year. One such hypothesis, a revival of ideas proposed by Zahnle and Walker (1987), suggests Earth's spin stalled in the Precambrian due to a competition between gravitational and thermal atmospheric tides, decelerating and accelerating Earth's spin, respectively. Thermal atmospheric tides are currently only a small fraction of the complete tidal pull on Earth, but in the past, they may have increased due to a resonance. I will present a review on the status of this controversy.

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Author: *Legnaro E.*

Speaker affiliation: Università di Genova, Dipartimento di matematica - DIMA

Title: Long-Term Dynamics of Lunar Satellites

Abstract

The exploration of the lunar space environment and the deployment of satellites around the Moon represent a critical frontier in space exploration.
This presentation will delve into the long-term dynamics (on the scale of years) of satellites orbiting the Moon, with a focus on secular resonances.
Specifically, we will show that the 2g resonance plays a crucial role in determining the operational lifespan of these satellites. After presenting numerical lifetime maps, we aim to understand the patterns observed on these maps through the development of an analytical model.
In addition, we will illustrate a key difference from the case of Earth-orbiting satellites: in the lunar orbit, satellites' re-entry does not follow from chaotic dynamics, but is instead dictated by the structure of the 2g resonance's phase portraits.

Author: *Liberato L.*

Speaker affiliation: Observatoire de la Côte d'Azur

Title: The known large NEOs' evolution into Centaurs

Abstract

Near-Earth objects (NEOs) evolution is known to be chaotic due to the frequent close encounters with the terrestrial planets. This population is sustained mainly by objects in the main belt. The overlap of Jovian and Martian resonances, combined with other non-gravitational effects such as YORP and Yarkovsky, cause a chaotic dynamical evolution of main-belt objects and eventually their transport into the inner-planets crossing region. Objects from outer regions, such as the centaurs also supply the NEO population. The centaurs are a transitional population of minor body objects with orbits among the giant planets and an estimated lifetime of the order of a few million years. The strong gravitational perturbations in the centaur's region lead most objects to an unpredictable evolution with unstable trajectories. The centaur population is believed to be composed mainly of objects that escaped from the Kuiper belt. The objects in the outer Solar System present a large spectral variety suggesting that the surface of these bodies suffered effects from different types of mechanisms, where one of them could be space weathering, indicating that some of them could have suffered more surface changes due to solar radiation than others. In Liberato et al 2023, we studied the dynamical evolution of 839 known NEOs with estimated diameters above 1km. We statistically identified preferential routes for the objects to be transferred among regions of the Solar System. We found that about 9% of the studied initial known NEO sample moved to the Centaurs region due to Jupiter's strong gravitational perturbation. It takes about 3 million years for these objects to move from the NEO region to the centaurs. Most of the bodies that reach this region are eliminated in a short time, while a few spend a considerable amount of time as centaurs. These objects present a median residence time of 100 thousand years as centaurs but about 2 Myrs on average. Therefore, it is likely that some of the bodies we find orbiting among the giant planets were once NEO, as suggested by spectroscopic data. In this presentation, I will present illustrative instances of orbital evolution, highlight the key characteristics that contribute to this type of behaviour and discuss the contribution of non-gravitational effects in this scenario.

Author: *Lippi M.*

Speaker affiliation: INAF - Osservatorio Astronomico di Arcetri

Title: Unveiling Chemical Links between Comets and Disks

Abstract

Comets accreted from the gas and dust in our protoplanetary disc approximately 4.6 billion years ago. Soon after formation, they were scattered and stored far enough away from the Sun, where they remained significantly frozen until this day, most likely maintaining larger part of their original mineralogical and chemical properties. In this view, comparing molecular abundances in comets to those in planet-forming disks surrounding young solar analogues can reveal significant insights in the physical, chemical, and evolutionary processes that shaped our and other planetary systems, including the degree of the chemical reprocessing in the disk (inherited vs reset scenarios) [1,2,3]. Recent cometary studies have revealed a wide chemical diversity among comets [1,4,5] which is consistent with the numerous processes that may have occurred in our protoplanetary disc, and with the dynamical models that predict the comets dispersion into their current reservoirs [6]. This makes it quite complicated to chemically classify these bodies and to link the observed differences to each comet's formation site. Here we present a statistical analysis of methanol, formaldehyde, and ammonia in 35 comets as measured by infrared high-resolution spectroscopy. Our research aims to: (i) search for significant differences across dynamical classes (e.g., Jupiter-family/short-period vs. Oort-Cloud/long-period comets) that could be linked to disk processes and/or comet material evolution after storage; and (ii) compare the molecular abundance ratios in comets with those measured in protoplanetary discs. We further investigate the reliability of the abundance ratios as probes of the cometary ice composition by looking at variations due to: (i) chemical or physical processes occurring in the coma during the observations, e.g., differences in outgassing before and after perihelion; (ii) modelling and/or instrumental effects, e.g. by comparing the comets' molecular abundance values estimated from infrared spectroscopy to those retrieved from observations at millimetre wavelengths [e.g., 7,8], as well as with 67P/Churyumov-Gerasimenko data collected using the Rosina mass spectrometer during the ESA-Rosetta mission [9]. Our analyses reveal a few trends correlated with the observing conditions, as well as differences among data obtained using different methodologies. While some of these differences are minor and can simply be explained by data variability, others are statistically significant and may drastically change our understanding of comet diversity in the context of planet formation. The overall findings will be discussed considering the chemical abundances of methanol, formaldehyde and ammonia observed in protoplanetary disks, to determine whether comets inherited material from the early stages of star formation. This will further highlight the significance of large sample statistics to properly constrain the range of molecular abundances in comets and disks prior to any comparison.

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Author: *Liu P.*

Speaker affiliation: University of Alicante

Title: Fission of asteroids through sudden spin-up events

Abstract

The evolution of rotation rates of small asteroids is subjected to mechanisms including (1) The Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect: a thermophysical process that arises from the anisotropic thermal re-radiation of absorbed sunlight from a non-axially symmetric surface, resulting in a net torque that can secularly modify the bulk rotation rate. (2) Off-spin-axis collisions by a small projectile: such collisions can change the spin state of an asteroid through the exchange between the projectile orbital angular momentum and the impacted body rotational angular momentum. (3) Planet/star close encounters: any asteroid can have close encounters with planets, or with its host star, which will change its rotation state due to tidal torques. The relative importance of each mechanism depends on the relative sizes, shapes, compositions, structures, and encounter geometries of the interactions.
Some studies show that the YORP effect may gently spin up small asteroids close to or beyond their breakup limit, causing gradual mass shedding from their surface, assuming the effect is constant and unaltered with time by bulk deformation or spin orientation changes. Alternatively, a single strong collisional event or strong tidal encounter may abruptly spin up the body well beyond the breakup limit, causing sudden fission. This process has not yet been investigated in detail with realistic asteroid structures, so we study sudden spin-up and fission events numerically. Asteroids are modelled as gravitational aggregates with an updated SS-DEM implementation of the PKDGRAV N-body gravity code for the handling of non-spherical components. This approach allows interlocking between real angular fragments in gravitational aggregates. We find that relatively large fragments and clumps may detach from the original body and potentially evolve into a binary system, asteroid pair, contact binary, or simply be disrupted, depending on the spin-up conditions.

Authors: *Makadia R.*, Chesley S. R., Farnocchia D., Eggl S.

Speaker affiliation: University of Illinois at Urbana-Champaign

Title: A novel method for computing state transition matrices using the unscented transform

Abstract

State Transition Matrices (STMs) are widely used in dynamical systems analysis, with applications ranging from optimal control theory to applied celestial mechanics such as orbit determination. Current methods of computing STMs for nonlinear systems are split into two categories: either the variational equations of the dynamics are integrated along with the nominal state to yield an analytic STM, or the STM is computed numerically using finite differences. Analytical derivatives for STMs are cumbersome to derive (or require automatic differentiation) and finite difference based STMs can be subject to accuracy limits set by the interplay between local truncation errors and finite floating-point precision.

In this work, we explore the use of unscented transforms to compute the STMs for nonlinear systems with specific application to asteroid orbit propagation and orbit determination. Compared to analytic STMs, our method does not require the implementation of complex partial derivatives or auto-differentiation of the dynamics. It also alleviates the need for finite differences that might not work in all situations (e.g., orbit propagation for main-belt asteroids as opposed to near-Earth asteroids or impactors). In terms of performance, the unscented transform STMs evaluate the same number of trajectories as first-order central differences, so the computational cost is no worse than finite difference STMs.

Preliminary results show that STMs computed using the unscented transform can be at least as accurate for long-term mapping of an off-nominal state compared to the analytic and numerical STMs. Furthermore, for asteroids with planetary close encounters, the mapping accuracy of certain unscented transform STMs does not instantaneously worsen. The invariance of the accuracy of the mapped state indicates that unscented transform-based STMs can be directly used in practical applications such as orbit determination and B-plane uncertainty mapping for asteroids with deep planetary encounters.

Author: *Magnanini A.*

Speaker affiliation: University of Bologna

Title: Galileo, Juno, JUICE and Europa Clipper radio science data joint analysis to study dissipation in Jupiter system

Abstract

Tidal dissipation stands as one of the primary factors in the establishment and development of a mean motion resonance between satellites. The dissipation processes occurring within Jupiter and its Galilean moons have been proposed as the main driving force behind the formation of the Laplace Resonance. These processes cause the migration of the moons' orbits, enabling them to gradually assume different orbital ratios over time, eventually resulting in the formation of a resonance. Furthermore, this same mechanism could lead to the termination of the existing resonance at present.

The Laplace resonance is fundamental to maintain the dissipation that provides the energy to make Europa and Ganymede ocean worlds; studying its stability is thus crucial to characterize the potential habitability of these moons.

The future JUICE and Europa Clipper missions will probe the Jovian system performing several flybys of the moons Europa, Ganymede, and Callisto. The precise radio tracking data will provide an accurate estimation of the gravity and ephemerides of the Galilean moons. This is especially true for Ganymede, after JUICE insertion in a low (500-200 km) circular orbit around the moon for at least four months, and for Europa, for which are scheduled more than 50 flybys from Europa Clipper. The evolution of the orbits of the Galilean moons will allow for an estimation of the dissipation in Jupiter at the orbital frequency of each Galilean moon, parameterized through the imaginary part of its degree-2 Love numbers. Unfortunately, the dissipations at the different satellite orbital frequencies are highly correlated due to the Laplace resonance, complicating their estimation, and Io which is the moon that dominates the evolution and dissipation of the Jovian system will never be flown by neither JUICE nor Clipper. For this reason the addition of the Juno Io's flybys, occurring on December 2023 and February 2024, respectively, together with the past mission Galileo, which performed more than 5 flybys of the moon, could be a fundamental addition to the data set. Moreover, their addition to JUICE and Europa Clipper increase significantly the time span of observation, improving the visibility of dissipative effects.

In this study, we analyze the attainable uncertainties for the parameters characterizing the dissipation in Jupiter's system and the ephemerides of the Galilean moons combining simulated range & range-rate radio tracking data from JUICE, Europa Clipper, Juno and Galileo showing the synergies and the relative improvements in the uncertainties and correlations of the joint analysis.

Author: *Marchi S.*

Speaker affiliation: SWRI, Boulder

Title: Lucy in the sky with Trojan asteroids

Abstract

Spacecraft have roamed far and wide across the Solar System, passing by numerous primitive small bodies from the orbit of the Earth to beyond the orbit of Pluto. There are two large populations of stable asteroids (estimated to contain more than a million objects larger than 1 km in diameter) that have yet to be explored at close range, the so-called Trojan asteroids, which lead and trail Jupiter by 60° along its orbit around the Sun where they persist due to a stabilizing resonance.
The exploration of the Trojan asteroids has been identified as a high NASA's scientific priority, and the Lucy mission will accomplish the first reconnaissance of these distant bodies. On its way to the Trojan asteroids, Lucy is bound to cross the Main Belt.
I will provide an update on the mission including results from a first flyby of Main Belt asteroid Dinkinesh, and discuss plans for the upcoming flyby of a second Main Belt asteroid, DonaldJohanson, in April 2025.

Author: *Mariani V.*

Speaker affiliation: Observatoire de la Côte d'Azur, Geoazur Lab., UCA

Title: Bayesian approaches for orbitography: application to fundamental physics

Abstract

Bayesian approaches and machine learning techniques are opening up new perspectives in inverse problems in all areas of physics. In the field of orbit determination, least-squares methods are widely used, but encounter difficulties when the uncertainties of the observations are poorly known, or when the dynamic model has too many parameters to solve for.
In this talk, we are going to present some applications of recently introduced concepts obtained in the domain of fundamental physics tests within the solar system, tackling the problem with a bayesian approach, combining Gaussian Processes and Markov Chain Monte Carlo methods in planet orbitography. We show how it is possible to get the posterior distribution of the mass of the graviton, taking into account the full dynamics of the solar system, with an improvement of more than one order of magnitude of its possible upper bound, with respect to the previous analogue results (Mariani et al. 2023, Bernus et al. 2020). Similarly, we test the Brans-Dicke class of scalar tensor theories: we find marginal evidence suggesting that the effect of violation of the Strong Equivalence Principle can no longer be assumed to be negligibile in planetary ephemerides with the current data (Mariani et al. 2024).
These results have been obtained in the context of the INPOP planetary ephemerides but the methods described above can be applied to any orbit reconstruction problem.

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Author: *Marò S.*

Speaker affiliation: Universidad de Oviedo

Title: Orbit Determination: from order to chaos

Abstract

We consider a problem proposed by Andrea Milani, in the framework of orbit determination. More precisely, we are interested in the accuracy of the orbit determination problem in the case of simultaneous increase in the number of observations and the time span over which they are performed. Numerical results obtained by Andrea Milani and collaborators suggested that the results depend on the dynamics and on the addition or not of a parameter to the initial conditions.
In this talk I will present some mathematical aspects of the problem highlighting the role of KAM theory and hyperbolic dynamics.

Authors: *Mastroianni R.*, Marchesiello A., Efthymiopoulos C., Pucacco G.

Speaker affiliation: European Space Agency (ESA)

Title: Bifurcations of periodic orbits in the 3D secular planetary 3-Body problem: an approach through an integrable Hamiltonian system

Abstract

We analyze, through a geometric description, the sequence of bifurcations of periodic orbits in an integrable Hamiltonian model derived from a normalization of the secular 3D planetary three body problem presented. Stemming from the results in [1], we analyze the phase space of the corresponding integrable Hamiltonian model. In particular, we propose a normal form leading to an integrable Hamiltonian whose sequence of bifurcations is qualitatively the same as the one in the complete system. Using a representation of the phase space in the 3D-sphere through Hopf variables ([2],[3],[4]), we geometrically analyze the sequence of bifurcations leading to the appearance of new fixed points of the secular Hamiltonian, i.e., periodic orbits in the complete system. Moreover, through a semi-analytical method, we find the critical values of the integral giving rise to the pitchfork and saddle-node bifurcations present in the system.

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Author: *Michel P.*

Speaker affiliation: Univ. Côte d'Azur, Obs. Côte d'Azur, CNRS, Lagrange Lab

Title: Space missions to asteroids: checking original ideas of Paolo Farinella and Andrea Milani

Abstract

We are currently living the golden age of asteroid exploration, thanks to the number of past, ongoing and future missions devoted to these objects. All these missions revolutionize our understanding of these fascinating bodies, which evolve in the challenging low gravity environment, and address research topics that were at the heart of researches of Paolo Farinella and Andrea Milani. Checking some of their original ideas is often the goal of these missions, and at the origin of projects that sometimes even lead to real missions. To name one, Andrea Milani was the science advisor of the Don Quixote project that, with my colleagues of the Near-Earth Object Advisory Panel (NEOMAP), we recommended to ESA as a priority in the framework of planetary defense initiatives in early 2000s. This project, which consists of testing the kinetic impactor technique to deflect asteroids and went into Phase A at ESA, paved the way to the NASA DART and ESA Hera missions, which eventually take place, with DART having already performed the first asteroid deflection test. In the late 1990s, Paolo Farinella initiated the ideas that the Yarkovsky effect may contribute to the evolution of asteroids, possibly helping them to be placed in unstable zones in the asteroid belt, leading them in the near-Earth space. Measuring the Yarkovsky effect was one of the goal of the NASA OSIRIS-REx mission to the asteroid Bennu, as well as understanding its origin, which relates, like most asteroid mission targets, to the collisional process that was one of Paolo's favorite topics. I will make a review of past, ongoing and future asteroid missions, making the link with Paolo's and Andrea's ideas, showing that their contributions have been major in the field and are still considered at the highest level in mission goals.

Author: *Mignard F.*

Speaker affiliation: OCA, Nice

Title: Dynamics of asteroids with Gaia

Abstract

The ESA spacecraft Gaia has been observing minor bodies of the Solar System since the start of the science mission in July 2014. Since then about 350,000 asteroids are regularly sampled with astrometric and spectrophotometric measurements and at mission completion in early 2025 this would amount to an average of 120 observations per body, more or less regularly distributed over the 125 months of the satellite operation. With a single astrometric measurement at the mas level, this will make a unique set of homogeneous and accurate positions. I will show the detailed content of this data base and discuss the properties of the orbital solution obtained with 66 months of data, together with the expectations with the 10-year coverage for the orbits and the masses of the most massive bodies.

Author: *Mochi M.*

Speaker affiliation: University of Pisa

Title: Yarkovsky effect investigations with Astroshaper and Orbit14: software synergies and relevance of shape effects

Abstract

Orbit14 is a reliable orbit determination software, developed by the Celestial Mechanics Group at the University of Pisa. It is currently being upgraded with new features to provide accurate orbit determination for the Hera mission. In particular, a new model for the Yarkovsky effect on Didymos is being included.

We present how the orbit determination process for Hera will rely on the synergy between Orbit14 and the thermophysical simulation software Astroshaper, developed by Dr. M. Kanamaru (University of Tokyo), to accurately account for the Yarkovsky effect. Moreover, using Astroshaper, we investigate the dependence of the Yarkovsky drift on the shape of the asteroid, by comparing simulations conducted using shape models with different levels of complexity.

Author: *Nobili A.*, Anselmi A.

Speaker affiliation: Università di Pisa

Title: A critical analysis of the first test of the Weak Equivalence Principle in space

Abstract

The Weak Equivalence Principle (or Universality of Free Fall) is the founding pillar of General Relativity and as such it should be tested as precisely as possible. For the first time ever the *Microscope* mission has tested it in low Earth orbit, finding that two test masses made of Pt and Ti fall towards the Earth with the same acceleration to about 1 part in 10^{15}, an improvement by about two orders of magnitude with respect to ground tests with torsion balances by the Eöt-Wash group. Even small space missions such as *Microscope* are expensive and hard to replicate; yet, the essence of Physics is repeatability. This work is a critical analysis of the *Microscope* results based on basic physics arguments and knowledge acquired from previous experiments. The focus is on the limiting thermal noise and the introduction of a large amount of artificial data (up to 35%, 40% of the sessions data). Our analysis of thermal noise reveals inexplicable anomalies which may in fact be due to a fluctuating sub-μV potential caused by electric patch charges. It should be carefully investigated because it gives rise to an unstable zero. The measurements show a large number of acceleration spikes related to the synodic frequency relative to the Earth (the frequency of the signal) and the Sun. They are removed, and the ensuing gaps are replaced with artificial data, which however retain memory of the spikes they have replaced and may therefore mimic a violation signal or cancel an effect (signal or systematic). An existing alternative approach relying solely on real measured data would make the result of the experiment fully robust and unquestionable. Key lessons for a major improvement in the future follow from this analysis.

Author: *Paoli R.*

Speaker affiliation: University of Pisa

Title: Analytical development of the mixed Yarkovsky effect for objects in a non-circular orbit

Abstract

The Yarkovsky effect is a thermal effect known which is relevant for many asteroids, as it causes a long-term variation of the semi-major axis of the asteroid. If the asteroid's rotational frequency ω_{rot} is much larger than its mean motion around the Sun n, the Yarkovsky effect decouples in two components, namely called *diurnal* and *seasonal* effects. The diurnal component is associated to ω_{rot} and it is maximum when the obliquity of the asteroid γ is equal to $0°$, while the seasonal component, associated to n, is maximum when $\gamma = 90°$. Depending on the value of γ, the diurnal effect can either increase ($90° < \gamma < 180°$) or decrease ($0° < \gamma < 90°$) the semi-major axis, while the seasonal effect can only decrease the semi-major axis. Analytical theories concerning the *mixed* Yarkovsky effect, which take into account also the coupled diurnal-seasonal terms, are available only for bodies in a circular orbit around the Sun. The work presented in this talk shows a possible way to extend the mixed Yarkovsky effect theory to objects with non-circular orbits, assuming Lambert's thermal emission, i.e. the thermal recoil force is normal to the surface. To achieve this, one first needs to solve for the *scaled average temperature* T'_{av} of the body along its orbit. In principle T'_{av} depends both on the eccentricity and the inclination. However, we show how further simplification can be made in the limit of large bodies, and prove that in this situation the scaled average temperature actually depends only on the eccentricity. Then one can use the deviations from the averaged temperature to obtain the mixed Yarkovsky effect analytically in a given inertial reference frame. Finally we conclude by applying the mixed Yarkovsky effect to known asteroids with $e \neq 0$ and comparing the decoupled effects to the coupled one in the context of the Hera mission, considering how the Yarkovsky effect acts on the major body of the Binary system (65803) Didymos.

Authors: *Perozzi E.*, Castronuovo M., Cirina C., Di Cecco A., Vellutini E.

Speaker affiliation: Agenzia Spaziale Italiana, Roma

Title: The Flyeye Telescope for Planetary Defence and Space Surveillance

Abstract

The so-called “Flyeye” is a new-generation 1-m aperture telescope which relies on an innovative optical design which splits the incoming light into 16 different channels, thus resulting in an extremely wide Field of View (approximately 45 square degrees). It is, therefore, best suited for timely detecting small-size asteroids approaching the Earth (the so-called “Imminent Impactors”) and for providing a high-performance optical sensor for cataloguing Earth orbiting satellites and space debris. The Italian Space Agency has strongly supported the development of the first Flyeye within the framework of the Planetary Defence activities of the ESA Space Safety Programme. Its realization has been carried out by a European consortium led by OHB-I and the telescope will be installed on Monte Mufara, within the area of Parco delle Madonie (Sicily). The selection of the site has been driven by the good sky quality, fully compliant with the Flyeye technical characteristics and purpose, while the observatory building has been especially designed to minimize the environmental impact. In order to carry out the commissioning and science verification phase in an ideal site from the logistic point of view, the telescope will undergo a temporary installation at the ASI Centre for Space Geodesy (CGS – near Matera, Italy). A network of at least three Flyeye telescopes properly distributed across the globe is expected to provide a significant contribution to NEO discoveries. The Flyeye design allows also surveying the sky for artificial space objects. In particular it represents an efficient way of complementing radar observations in the High-LEO region (1000-2000 km altitude), and to build-up and maintain a catalogue of MEO (10000-20000 km altitude) objects above a threshold size of 35 cm. These unique characteristics have brought ASI to the procurement of four Flyeye telescopes for space surveillance. They are going to represent a major Italian contribution to the EU SST (Space Surveillance and Tracking) initiative, whose goal is to ensure Europe a high level of autonomy in providing SST services. The Flyeye concept pays tribute to Andrea Milani for having first envisaged and demonstrated the benefits of such a wide-field high-sensitivity telescope for both, Planetary Defence and Space Surveillance applications, and for having named it accordingly.

Author: *Pilat-Lohinger E.*

Speaker affiliation: University of Vienna

Title: The flyby of Gliese710 and its impact on Oort cloud comets

Abstract

In about 1.3 million years, the K star Gliese 710 will approach our Sun up to 10500 au and pass through the Oort Cloud. This will disturb the comets in this area and they will either escape into interstellar space on hyperbolic orbits or advance towards the Sun. N-body calculations for the period of the stellar flyby are used to show these orbital changes. The use of the GPU N-body code GANBISS enables calculations for up to 50 million comets. This allows simulations to be made for a higher density of comets in this area, which provides better statistics on the scattering of the comets.

Author: *Pinzari G.*

Speaker affiliation: Università di Padova

Title: Three canonical maps reducing the SO(3) symmetry

Abstract

The SO(3) symmetry in N-body problems is a serious obstacle to the application of perturbation theories to unrestricted N-body problems. As an example, it prevented the direct application of the theorem of Kolmogorov over about 50 years in the case $N \geq 4$.
We review recent maps which do this job, which however seem still not much known in the community.

Author: *Polimeni D.*

Speaker affiliation: Università degli studi di Torino

Title: On the existence of minimal expansive solutions to the N-body problem

Abstract

We deal, for the classical N-body problem, with the existence of action minimizing half entire expansive solutions with prescribed asymptotic direction and initial configuration of the bodies. We tackle the cases of hyperbolic, hyperbolic-parabolic and parabolic arcs in a unitary manner. Our approach is based on the minimization of a renormalized Lagrangian action, on a suitable functional space. With this new strategy, we are able to confirm the already-known results of the existence of both hyperbolic and parabolic solutions, and we prove for the first time the existence of hyperbolic-parabolic solutions for any prescribed asymptotic expansion in a suitable class. Associated with each element of this class we find a viscosity solution of the Hamilton-Jacobi equation as a linear correction of the value function. Besides, we also manage to give a better description of the growth of parabolic and hyperbolic-parabolic solutions.

Author: *Pucacco G.*

Speaker affiliation: Università di Roma Tor Vergata

Title: Preferred frames and geodetic satellites

Abstract

We present possible effects of preferred frames on satellite orbits tracked with high-precision laser ranging. We aim at testing the local-boost invariance of gravitational interaction.
The analysis, based on a Hamiltonian approach, allows us to get the evolution of perturbed Keplerian elements in terms of the velocity of the satellite with respect to a global reference frame possibly selected by the cosmological matter distribution.

Author: *Rodríguez del Río Ó.*

Speaker affiliation: Universitat Politècnica de Catalunya

Title: Tracing Celestial Rhythms: Mean Motion Resonance of Hyperion and Titan

Abstract

The interaction between Hyperion and Titan demonstrates a phenomenon known as mean motion resonance. This occurs when the orbital periods of two celestial bodies form a ratio of small integers, leading to regular gravitational interactions that affect their orbits. In the case of Hyperion and Titan, their mean motion resonance is characterized by a 3:4 ratio, indicating that for every three orbits completed by Hyperion, Titan completes approximately four orbits. Titan, as Saturn's largest moon, exerts a dominant gravitational influence due to its size and proximity to Saturn. In contrast, Hyperion is much smaller and orbits farther from Saturn. This configuration lends itself well to modeling using the RTBP (Restricted Three-Body Problem). In this presentation, we will discuss how we can incorporate JPL data into our mathematical model, enabling us to numerically compute the periodic and quasi-periodic orbits believed to govern their motion. To calculate these quasi-periodic orbits, also known as invariant tori, we utilize temporal or spatial Poincaré sections. We have conducted various comparisons to determine the most suitable and efficient approach for analyzing these invariant structures and their stability.

This work is a small tribute to Paolo Farinella and Andrea Milani and stems from their article "Resonances and close approaches. I. The Titan-Hyperion case".

Author: *Rossi M.*

Speaker affiliation: University of Genoa

Title: Detection of fast close encounters with Kustaanheimo-Stiefel regularized fast Lyapunov indicators in the elliptic restricted three-body problem

Abstract

We discuss the use of regularized fast Lyapunov indicators (RFLIs) in the elliptic restricted three-body problem (ER3BP) to study a category of transits through the Hill's sphere of the secondary body (fast close encounters). Starting from the theoretical development of the Kustaanheimo-Stiefel (KS) regularization of the ER3BP in the synodic rotating-pulsating reference frame, we use the KS-regularized Hamiltonian to recover a definition of fast close encounters for small values of the mass parameter (while we do not require a smallness condition on the eccentricity of the primaries). We show that for these encounters, the solutions of the variational equations are characterized by an exponential growth during the fast transits through the Hill's sphere. Thus, for small values of the mass parameter, we justify the effectiveness of RFLIs to detect orbits with multiple fast close encounters. Finally, we provide numerical demonstrations showing the benefits of the regularization in terms of computational cost and close encounter detection in the Sun-Jupiter and Sun-Earth system.

Author: *Saillenfest M.*

Speaker affiliation: IMCCE, Paris

Title: Tilting Uranus without giant impact - a recent perspective

Abstract

On a gigayear timescale, the tidal migration of moons can gradually tilt the spin axis of their planet. This mechanism has been shown to be effective for Jupiter and Saturn, and it may have played a role in increasing the obliquity of Uranus to its current value (98°). This scenario can have a high probability of reproducing the current spin state of Uranus, but it requires Uranus to have had a big former moon (with a mass ranging from those of Europa and Ganymede) and a very high internal tidal dissipation. In this talk, I will discuss the prospect of alleviating these strong constraints by taking into account the interaction between several moons.

Author: *Scheeres D.*

Speaker affiliation: University of Colorado Boulder

Title: What's Up with YORP? Identifying inconsistencies between theory and observation

Abstract

The YORP effect has been identified as one of the major drivers for the mechanical evolution of small, rubble pile asteroids. The predicted effect has also been detected for a growing number of small bodies, with magnitudes of spin-up roughly consistent with the predicted physics of photon momentum transfer to a body. In fact, the detailed physics of this effect has also been explored, with a number of different components to the YORP effect having been identified, depending on a body's thermal inertia, surface roughness and overall asymmetric shape. It is significant that some of these additional effects have been needed to explain the detailed observations of the YORP effect to date. In tandem with our better understanding of the physics of the YORP effect, are dynamical studies that have identified key trends which should exist for the spin states of bodies that are being driven by YORP. However, a simple comparison of the global predictions for small body spin state solutions with the observed population shows some significant disconnects, which may point out the need for a revised understanding of this effect.

This talk will focus on some of the key disparities that are seen between the observed population of small, rubble pile asteroid spin states and the natural predictions of dynamical evolution from different models of the YORP effect. These disparities represent a challenge for our understanding of this effect, the resolution of which will have significant impacts on our understanding of the dynamical evolution of the solar system.

Author: *Spoto F.*

Speaker affiliation: Center for Astrophysics, Harvard and Smithsonian

Title: The Minor Planet Center: recent improvement and future developments

Abstract

The Minor Planet Center (MPC) is a NASA funded project that operates at the Smithsonian Astrophysical Observatory and is the single worldwide location for receipt and distribution of positional measurements of minor planets, comets and outer irregular natural satellites of the major planets (https://minorplanetcenter.net/).

The observed data, orbital elements, and MPC-generated products are publically available through a variety of web-posted files and tools, but are also now being made available via replication of a live, postgres database that is populated as part of the processing of each submission. Use of a database-centric system is essential to increase capacity and provide the processing speed necessary to cope with planned future surveys (e.g. VRO/LSST and NEO Surveyor).

We would like to present our most recent efforts. Those include, but are not limited to:

- Improving our processing pipelines;
- Improving the usability of our observation and orbit database tables;
- Increasing the level of validation of our products, such as observations and orbits;
- Making our website more user friendly and improving our communication system.

Particular attention will be devoted to presenting the main orbit determination pipeline, including the use of the OrbFit orbit determination software to produce our orbit catalogs.

Author: *Tanga P.*

Speaker affiliation: Observatoire de la Côte d'Azur

Title: Combining Gaia astrometry and photometry: an asteroid survey for shapes, rotational properties and binaries

Abstract

The accuracy of the astrometry by the Gaia mission of ESA contains several signatures related to the physical properties of the observed asteroids. On one hand, their presence requires to take them into account for the best exploitation of the observations, in the domain of dynamical studies. On the other, they can disclose the possibility of getting new constraints, for a large number of objects, on scattering properties, shapes and presence of satellites. These capabilities are even further multiplied when coupled to the inversion of the wide-band photometry obtained by Gaia itself, yielding a new sample of pole coordinates and rotation periods. We will discuss results from a first systematic search of asteroids satellites, performed by studying the presence of periodic variations (wobble) in the astrometric residuals to the orbital fit. A list of several best candidates is obtained, revealing the potential to explore categories of binary asteroids that are not accessible by other techniques. When wobble periods are compared to photometric periods, a number of candidate synchronous binary systems is revealed in this sample, awaiting for confirmations.

Author: *Toliou A.*

Speaker affiliation: Luleå University of Technology

Title: Resonances that bring asteroids close to the Sun and into super-catastrophic disruption

Abstract

Mean motion and secular resonances between near-Earth Asteroids and the terrestrial and giant planets are, typically, able to dramatically increase the eccentricities of the asteroids. In addition, it is expected that NEAs that reach sufficiently (but not trivially) close to the Sun will undergo a super-catastrophic disruption, for which the responsible mechanisms are still undetermined and under investigation. Using numerical simulations of a synthetic NEA population, we are able to identify which resonances are the most significant in lowering the perihelion distances of NEAs close to the Sun. Moreover, we can determine how each resonance relates to the dynamical lifetimes of the asteroids when they reach small heliocentric distances and calculate the average time they spend there. The biggest motivation behind this study is to help guide theoretical and experimental work that aims to understand the disruption mechanism.

To do so, we have developed an algorithm that automatically identifies occurrences of mean motion and secular resonances during the orbital evolution of the synthetic NEA population. Our main results are that the 3:1 and 4:1 mean-motion resonances with Jupiter, as well as the secular resonances ν_6, ν_5, ν_3 and ν_4 are the typical culprits bringing the orbits of NEAs close to the Sun. The time-scale of the small-perihelion evolution is fastest for the 4:1J, followed by the 3:1J, while ν_5 is the slowest resonant mechanism. Finally, our algorithm fails to identify a resonant mechanism for ~ 7 % of the asteroids of our synthetic population during the last stages of their dynamical evolution. This suggests that either the secular oscillation of the eccentricity due to the Kozai mechanism, a planetary close encounter or another resonance that we did not include in our study pushed them close to the Sun and into super-catastrophic disruption.

Author: *Tsiganis K.*

Speaker affiliation: Aristotle University Thessaloniki

Title: Secular theory and semi-analytical propagation of lunar orbiters

Abstract

We present the development of a secular theory and the implementation of a semi-analytical propagator for lunar orbiters, under various perturbing effects. The stability and low-cost maintenance of low lunar satellites was among the topics pioneered by Andrea Milani who, together with Zoran Knežević advanced the theory and application of selenocentric proper elements for mission design in the 90's. The higher-degree theory that is presented here was developed using canonical perturbation theory in the form of Lie series computed in 'closed form', i.e. without expansions in the satellite's orbital eccentricity, leading to efficient averaging of the short-periodic terms in the satellite's motion, arising from various perturbations. The averaged equations of motion can be propagated numerically, while short-periodic corrections can be added a posteriori, using the generating functions of the transformations. The theory was tested with an in-house developed, semi-analytical propagator on a large sample of potential mission orbits around the Moon. The results show a median cumulative position error of only $\sim$ 10km after 365 days of propagation, complementing the advantage of high computational efficiency of a semi-analytical propagator.

The SELENA (SEmi-anaLytical intEgrator for a luNar Artificial satellite) propagator was developed under the CNES R&T R-S20/BS-0005-062 contract.

Author: *Tsirvoulis G.*

Speaker affiliation: Luleå University of Technology

Title: Thermal disruption of NEAs: Experimental results based on CI asteroid simulants

Abstract

Over the past few years, the activity displayed by near-Earth asteroids has become the focal point of a considerable number of studies. From NEA population models (e.g. Granvik et al. 2016), observational results (e.g. Jewitt et al. 2013, Wiegert et al. 2020, Lauretta et al. 2019), numerical investigations (e.g. Molaro et al. 2020) and experimental efforts (e.g. Delbo et al. 2014, Masiero et al. 2021) it is evident that the activity of NEAs, and more specifically the thermally driven component, can provide useful insights on physical properties such as the bulk composition and internal structure of these objects.
We present the first results of our experiments conducted using SHINeS, a first of its kind space simulator developed to specifically study the effects of direct insolation of high intensity on asteroid analogue materials (Tsirvoulis et al. 2022). For this line of experiments we used samples of a CI-type asteroid simulant (Britt et al. 2019) and studied the processes that lead to its disruption at heliocentric distances in the range from 0.08 to 0.23 AU. High-speed footage of the experiments allowed us to examine the nature of the disruption mechanisms and the rate of disruption as a function of the simulated heliocentric distance, in an effort to assess the effectiveness of direct thermal disruption of NEAs during their perihelion passages.

AuthorS: *Vartolomei T.*, Celletti A., Rodriguez-Fernandez V.

Speaker affiliation: University "Al. I. Cuza" of Iași

Title: Supervised and Unsupervised Machine Learning Techniques within the Space Debris Problem

Abstract

We merge classical and modern techniques by combining perturbative methods and machine learning algorithms. We provide an application to the Space Debris problem, computing different sets of elements (mean and proper elements) and applying existing clustering. The aim of this work is to analyze and find the most suitable method for grouping fragments generated after some simulated catastrophic events. Furthermore, we take into account the evolution of the orbital elements (osculating, mean and proper), uncertainties that could appear in observations and specific dynamical properties, combining the existing clustering methods with appropriately defined metrics.

Author: *Vavilov D.*

Speaker affiliation: IMCCE, Paris

Title: Semi-linear impact probability estimation of NEOs with the Earth

Abstract

The methods for estimating the impact probability of near-Earth objects with the Earth can be divided into two types: linear and non-linear. The non-linear methods, such as the Monte-Carlo method or Line of Variation sampling (LOV), require integration of a large set of orbits of virtual asteroids. In linear methods only the nominal orbit needs to be propagated, however, the methods cannot take into account close encounters with major planets. Here we present a semi-linear approach, where we need to integrate only several orbits of virtual asteroids but can handle moderate gravitational perturbations from major planets.

Author: *Vokrouhlicky D.*

Speaker affiliation: Institute of Astronomy, Charles University, Prague

Title: Jupiter Trojans: A few news and some views

Abstract

Jupiter Trojans (JTs) librate about the Lagrangian stationary centers L4 and L5 associated with this planet on typically small-eccentricity and moderate-inclination heliocentric orbits. The physical and orbital properties of JTs provide important clues about the dynamical evolution of the giant planets in the early solar system, as well as population of planetesimals in their source region. This talk aims to review at least a part of a significant progress in our understanding of JTs. A special attention will be paid to JTs orbital architecture and magnitude distribution. I believe this topic fits well the celebration of Andrea and Paolo legacy: Andrea's 1993 CMDA paper was the first modern attempt to shed light onto the orbital structure of JTs, while Paolo gave it a special touch with a daring hypothesis discussed towards the end of that work.

Author: *Voyatzis G.*

Speaker affiliation: Aristotle University of Thessaloniki

Title: Periodic-like terminator spacecraft orbits in a binary asteroid system. An application to Didymos-Dimorphos system

Abstract

Terminator orbits are a special type of spacecraft orbits located around an asteroid or a comet. They are formed under the balance between the gravity and the solar radiation pressure (SRP) and their plane is almost perpendicular to the direction towards the Sun. Such orbital configurations have a lot of advantages for space missions, e.g. stability, good observation of the asteroid system, non-interruptive communications with a mother spacecraft. Scheeres (1999) introduced terminator orbits as frozen orbits in an averaging approximation where the asteroid moves in an elliptic orbit around a Sun. In this study we consider a binary asteroid system and we approach terminator-like orbits as polar periodic orbits which belong to particular 3D-families of a circular restricted three body problem. It happens such polar orbits to have periods that permit their analytic continuation with respect to the eccentricity of the binary and the SRP. So, terminator-like orbits are obtained, and apart from their linear stability, the long-term stability is investigated numerically by considering the elliptic motion of the binary around the sun. In our computations the parameter values of the Didymos-Dimorphos system are used and SRP values for the Hera mission spacecrafts.

Author: *Vovk M.*, Brown P., Vida D.

Speaker affiliation: Western University

Title: Enhancing Satellite Impact Risk Assessments through Automated Meteoroid Fragmentation Analysis by the Canadian Automated Meteor Observatory

Abstract

This study explores the ablation and fragmentation of millimeter-sized meteoroids in Earth's atmosphere, processes crucial for understanding their physical properties and assessing satellite impact risks. These meteoroids act as proxies for their larger counterparts—comets and asteroids—whose properties are challenging to measure directly.

We aim to apply the erosion fragmentation model in an innovative, automated analysis of high-resolution observations of the Perseids meteor shower. Utilizing advanced meteor tracking instruments from the Canadian Automated Meteor Observatory, including telescopic mirror-tracking systems and Electron Multiplying CCD (EMCCD) HNü 1024 cameras, along with a comprehensive dataset of synthetic meteor observations.

By matching observed to synthetic data using Principal Component Analysis (PCA), we facilitate a nuanced estimation of meteoroids' physical parameters. The method's validity is demonstrated through the precise definition of each meteor's bulk density, erosion altitude, and ablation coefficients. Analyzing one million simulated events, we refine the error margins for meteoroids' physical traits, narrowing down to events that closely resemble the observed data. This approach underlines the importance of selecting appropriate observable components for PCA, significantly reducing the variance in erosion onset heights compared to manually derived values.

This investigation marks the first automated, statistically rigorous application of a meteoroid fragmentation model against high-resolution meteor observations, confirmed by consistent physical properties observed in Perseids meteoroids. Our goal is to integrate these findings into the next update of the NASA Meteoroid Engineering Model (MEM) by 2025, significantly improving its accuracy in predicting satellite impact risks.

Author: *Zhou W.*

Speaker affiliation: Observatoire de la Côte d'Azur

Title: The Yarkovsky effect on binary asteroids

Abstract

We explore the Yarkovsky effect on binary asteroids. While significant attention has been given to the binary YORP (BYORP) effect, the Yarkovsky effect is largely overlooked. The Yarkovsky effect for a planet-satellite system was previously studied for the Earth satellite LAGEOS by Rubicam (1982), Milani et al (1988), Farinella & Vokrouhlicky (1996) but not studied in detail for binary asteroids although it has been noticed by Vokrouhlicky et al (2005). We develop an analytical model for the binary Yarkovsky effect, considering both the Yarkovsky-Schach and planetary Yarkovsky components, and verify it against thermophysical numerical simulations.

Our analysis predicts new evolutionary tracks for binaries. For a prograde asynchronous secondary, the Yarkovsky force will migrate the satellite towards the location of the synchronous orbit on a timescale ($\sim$0.1 Myr), providing new insights into the synchronization mechanism of binary asteroids. For retrograde secondaries, the Yarkovsky force always migrates the secondary outwards. Satellites spinning faster than the Roche limit orbit period ($\sim$4.3 h) will migrate inwards until they disrupt, reshape, or form a contact binary. We also predict a short-lived equilibrium state for asynchronous secondaries where the Yarkovsky force is balanced by tides. Since the Yarkovsky force always migrates retrograde secondaries outwards, this process could form asteroid pairs having opposite spin poles. We provide calculations of the Yarkovsky-induced drift rate for known asynchronous binaries. We speculate that the Yarkovsky force may have synchronized the Dinkinesh-Selam system after a possible merger of Selam's two lobes. If the NASA DART impact broke Dimorphos from synchronous rotation, we predict that Dimorphos's orbit will shrink by $\dot{a} \sim 7$ cm yr^{-1}, which can be measured by the Hera mission.

Author: *Zimmermann M.*

Speaker affiliation: University of Vienna, Department of Astrophysics

Title: Planetesimal and planetary embryos interactions in inclined binary star systems: An investigation of collision velocities and impact angles

Abstract

Our study shows the dynamical evolution of a planetesimal and planetary embryo disc located in an inclined S-type binary star configuration. The disk contains up to 2000 planetesimals and 25 Moon to Mars sized planetary embryos and is located between 1 and 4 au around the primary star. We assume that the gas has already been depleted, thus only gravitational interactions are considered. Different configurations of the two solar type stars are considered with variation of the semi major axis (30, 60, and 100 au), the eccentricity (0.0, 0.2, and 0.4), and the inclination ($20°, 45°$, and $60°$) of the binary star system.
Previous calculations showed that over time, the disk objects spread across a range of $0°$ to $2i_b$, where i_b represents the inclination of the secondary star relative to the primary-disk orbital plane. Therefore, in this investigation, we use the orbital parameters of such a previously evolved embryo/planetesimal disk and study the full gravitational interactions by applying our recently developed GPU N-body code GANBISS, which is a highly parallelized implementation of the Bulirsch-Stoer method on a GPU. This numerical study focuses on the impact parameters of the disk objects, which are crucial for terrestrial planet formation.

Author: *Zopetti F.*

Speaker affiliation: Observatorio Astronómico de Córdoba - Universidad Nacional de Córdoba

Title: Resonant transport of Pluto's minor moons enabled by a post-impact water-vapor disk

Abstract

The formation of Pluto's satellite system was probably the result of a Giant Impact on a primordial body. Impact simulations are capable of simultaneously forming an intact Charon and a compact ice-rich debris disk. However, four minor moons were recently observed in the system in much wider orbits and remarkably close to $N/1$ mean-motion-resonances with Charon (with $N = 3, 4, 5$ and 6). The hypothesis of resonant transport of debris as Charon's orbit tidally expands is the simplest explanation for the small moon's distant and quasi-resonant orbits, but so far no mechanism has been found to reproduce this process and explain their current orbital configuration. In this paper we show that a post-impact water vapor disk, similar to the one that has recently been proposed for the formation of the moons of Uranus, can stabilize a large-scale resonant transport of small moonlets through aerodynamic drag. Despite the dynamical complexity of the mean-motion resonances, requiring a complex interwoven, we are able to transport four moon-analogs to orbits very similar to the observed ones, using standard hydrodynamical parameters of the disk and tidal factors of the binary components.