ABSTRACT BOOK

Complex Planetary Systems II
Kavli-IAU Symposium 382

July 3-7, 2023

CPS2

All the planetary systems, from the Earth-Moon system to the extrasolar ones, are complex systems, requiring several levels of expertise and interdisciplinarity to be clearly understood. Following the success of Complex Planetary Sytems in 2014, CPSII aims to bring forward the latest findings obtained in that perspective and to generate new collaborations between different disciplines for the future. Any astronomer involved in planetary systems, at any level, is invited to participate to the meeting and to propose its own expertise in future complex challenges.

Key topics

- Formation of planetary systems
- Long-term evolution and stability of planetary systems
- Exoplanets, climate and interiors
- Dynamics of resonances and observations
- Small bodies dynamics
- Orbit propagation methods
- Rotation of planets and satellites
- Dynamics of space debris

Scientific Organizing Committee
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PROGRAM

MONDAY 3

8h00–9h20 **Registration**

9h20–9h40 **Welcome & Opening remarks** Anne-Sophie Libert (chair of the SOC)

9h40–10h20 A. Morbidelli, *Interdisciplinarity: an effective approach to comprehending the formation of planetary systems*

10h20–11h00 **Coffee break**

11h00–11h40 D. Scheeres, *Binary Asteroids: A Pathway to Understanding the Morphological Evolution of Rubble Pile Asteroids*

11h40–12h20 D. Fabrycky, *Resonant Chain Dynamics: Interpretation of Observations*

12h20–12h25 A. Füzfa, *The UNamur observatory*

12h25–14h00 **Lunch**

14h00–15h40 **Parallel session - S01**

- D. Vavilov, *Partial Banana Mapping: search for close encounters and impact probability*
- L. Benet, *Transversal Yarkovsky acceleration for Apophis exploiting automatic differentiation tools*
- Ch. Lhotka, *On the Celestial Dynamics of Charged Dust in the Solar System*
- D. Ragozzine, *Non-Keplerian Motion of Trans-Neptunian Binaries: Shapes, Spins, and Formation*
- E. Pilat-Lohinger, *Inward and outward scattering of Oort cloud comets due to Gliese 710*

14h00–15h40 **Parallel session - PA02**

- B. Kumar, *Europa-Induced Overlapping of Secondary Resonances in the 4:3 Jupiter-Ganymede Unstable Resonant Orbit Family*
- A. Rodriguez, *Mapping the structure of the planetary 2:1 mean motion resonance: the TOI-216, K2-24, and HD27894 systems*
- G. Pucacco, *Normal forms for Laplace-like resonances*
- S. Gomes, *The passage through the 5:3 resonance between Ariel and Umbriel with inclination*
- Z. Knežević, *Secular resonance maps*

15h40–16h20 **Coffee Break**

16h20–17h00 **Parallel session - S01**

- S. Dermott, *Asteroid family membership in the inner belt*

- B. Sicardy, *Resonances around small bodies of the solar system: where should be the rings?*

16h20–17h00 **Parallel session - PA02**

- E. Kokubo, *Orbital Architecture of Planetary Systems Formed by Gravitational Scattering and Collisions*
- J. Mah, *Forming Super-Mercuries: Role of stellar abundances*

18h00–20h00 **Welcome Reception** - Boat tour

TUESDAY 4

9h00–9h40 M. Granvik, *Destruction mechanisms for near-Earth objects*

9h40–10h20 A. J. Rosengren, *On the Multiscale Astrodynamics of Cislunar xGEO Space*

10h20–11h00 **Coffee break**

11h00–12h20 **Parallel session - S01**

- S. Di Ruzza, *Analysis of co-orbital motion of real asteroid in a medium-term timescale*
- E. Legnaro, *MEO Secular Resonances: Phase Space, Eccentricity Growth and Diffusion of Navigation Satellites*
- G. Lari, *Orbital evolution of the Galilean moons driven by a fast orbital expansion of Callisto*
- C. Grassi, *Revisiting the computation of the critical points of the squared distance between two ellipses with a common focus*

11h00–12h20 **Parallel session - PA02**

- S. Crespi, *Terrestrial Planet formation Simulations: Homogeneous Comparison between Methods*
- Ph. Griveaud, *Migration of giant planets in low viscosity discs and consequences on the Nice model*
- N. Haghighipour, *Secular Resonances and Terrestrial Planet Formation in Planetary Systems with Multiple Stars: Theory and Application*
- G. Pichierri, *Forming the Trappist-1 system in two steps during the recession of the disc inner edge*

12h20–14h00 **Lunch**

14h00–14h40 A. Johansen *Forming planetary systems via pebble accretion*

14h40–15h40 **Round table "Space awareness"**

A. Rosengren, *Space debris dynamics*
J.-M. Van Nypelseer, *An initiative in space debris removal*
D. Hestroffer, *Hazardous asteroids and the Hera mission*

C. Linard, *Mapping population from space*
Y. Nazé, *Food for thought*

15h40–16h20 **Coffee Break**

16h20–17h00 **Parallel session - S01**

- M. Rossi, *Dynamical asymmetries for L4/L5 captures*
- G. Tommei, *On the predictability horizon in Impact Monitoring of NEOs*
- N. Torii, *Gap Structure Created by Satellite Embedded in Saturn's Ring*
- J. Li, *An overview of the high-inclination resonant population in the Kuiper belt*

16h20–17h00 **Parallel session - PA02**

- A. Courtot, *Chaos in meteor showers: the example of Draconids, Leonids and Taurids*
- Al. Petit, *Challenges of the catalogue building and maintenance based on optical survey of tge LEO region*
- M. Romano, *Network perspective to study the state of Earth's orbital traffic*
- M. Farhat, *The Impact of Laplace Surface Dynamics on Debris Disc Architecture*
- A. Dgokas, *Secular evolution of debris in highly eccentric and inclined orbits*
- A. Celletti, *SIMPRO: a simulator of breakup events and propagation of orbits of space debris*

WEDNESDAY 5

9h00–9h40 C. Gales, *Dynamics modelling and stability analysis of satellites orbiting oblate bodies*

9h40–10h00 **Poster flash talks 1-20**

10h00–11h00 **Poster session & coffee break**

11h00–11h40 K. Batygin, *Towards a Unified Model of Planet Formation*

11h40–12h20 D. Lay, *Hot Jupiters and Super-Earths: Spin-Orbit Puzzles in Exoplanetary Systems*

12h25–14h00 **Lunch**

14h00–14h40 E. Bolmont, *A journey from planets to stars: improving tidal models in orbital evolution codes*

14h40–14h50 A few words by Anne

14h50–15h50 **Parallel session - S01**

- C. Charalambous, *Tidal effects in resonant chains of close-in planets*
- A. Revol, *Dynamical evolution and heat dissipation in the Trappist-1 system*

- T. Ghosh, *Dynamical Instabilities and the Orbits of Kepler's Multis*

14h50–15h50 **Parallel session - PA02**

- M. Yseboodt, *Mars rotational elements and their quadratic behavior*
- M. Saillenfest, *Oblique rings as a natural end state of migrating exomoons*
- X. J. Xi, *Analytical representation for the numerical ephemeris of Titan within short time spans*

15h50–16h30 **Coffee Break**

16h30–17h30 **Parallel session - S01**

- A. Leleu, *Recovery and characterisation of resonant terrestrial planets hidden in transit surveys*
- J. Korth, *Hot Jupiters and their nearby surroundings*
- Th. Baycroft, *The BEBOP search for circumbinary planets in radial velocity*

20h00–22h00 **Vera Rubin show** - Le Delta

THURSDAY 6

9h00–9h40 G. Baù, *Alternative state representations for orbit prediction*

9h40–10h00 **Poster flash talks 21-36**

10h00–11h00 **Poster session & coffee break**

11h00–12h20 **Parallel session - S01**

- M. Efroimsky, *Pathways of Survival of Exomoons and Inner Exoplanets*
- N. Georgakarakos, *Dynamical habitable zones for circumbinary planets.*
- V. Christiaens, *A new directly imaged giant planet*
- Y. Suto, *Dynamics of a triple system comprising an inner binary black hole in a mutually inclined orbit.*

11h00–12h20 **Parallel session - PA02**

- S. Hadden, *Celestial Mechanics with the celmech code*
- J. Daquin, *Quantifying chaos with geometrical indicators*
- F. Gronchi, *Initial orbit determination from one position vector and a very short arc of optical observations*
- D. Hernandez, *Switching integrators reversibly in the astrophysical N-body problem*

12h20–14h00 **Lunch**

14h00–14h40 C. Dorn *Planet cores store majority of planetary water budgets*

14h40–15h40 **Round table "Habitability"**

E. Bolmont, *Habitable worlds and climate*
M. Gillon, *Future detections of habitable worlds*
E. Javaux, *From early Life to Habitability*
V. Debaille, *Life and meteorites*
B. Hespeels, *Rotifers in space*

15h40–16h20 **Coffee Break**

16h20–17h00 A. Correia, *New methods to study the tidal evolution of planetary systems*

17h00–17h40 R.-M. Baland, *The obliquity of Mercury: Models and interpretation*

19h00–22h00 **Gala dinner** - Brasserie François

FRIDAY 7

9h00–9h40 J.-B. Delisle, *Planetary systems in resonant chains*

9h40–10h20 C. Petrovich, *Long-term evolution of exoplanet systems*

10h20–11h00 **Coffee break**

11h00–12h20 **Parallel session - S01**

- F. Mogavero, *Timescales of chaos in the inner Solar System: Lyapunov spectrum and quasi-integrals of motion*
- R. Mastroianni, *The phase-space architecture in the secular 3D planetary three-body problem*
- N. Todorović, *Encounter manifolds in the Solar System. Preliminary results*
- T. Hayashi, *Lagrange stability of triple systems: disruption timescale distribution and its dependence on the orbital parameters*

11h00–12h20 **Parallel session - PA02**

- J. Rekier, *Resonantly amplified tidal dissipation in the fluid layers of planets and moons*
- F. Zoppetti, *Tidal orbital evolution of circumbinary planets*
- E. Valente, *Excitation of the obliquity of Earth-like planets via tidal forcing*
- A. Coyette, *Cassini States of Ganymede and Callisto*

12h20–14h00 **Lunch**

14h00–14h40 A. Petit, *Long-term stability of compact planetary systems*

14h40–15h20 N. Rambaux, *Lunar reference system from science to MoonLight and LunaNet*

15h20–16h00 **Coffee Break**

16h00–16h40 M. H. Lee, *Dynamics of Circumstellar Planets in Binary Star Systems*

16h40–17h20 J. Laskar, *The AstroGeo project*

17h20-17h30 **Closing Remarks**

	Monday	Tuesday	Wednesday	Thursday	Friday
8h	REGISTRATION	REGISTRATION	REGISTRATION	REGISTRATION	REGISTRATION
9h		**GRANVIK**	**GALES**	**BAU**	**DELISLE**
9h20	OPENING SESSION				
9h40	**MORBIDELLI**	**ROSENGREN**	**Poster flash talks**	**Poster flash talks**	**PETROVICH**
10h00					
	COFFEE BREAK	COFFEE BREAK	COFFEE BREAK + POSTERS	COFFEE BREAK + POSTERS	COFFEE BREAK
11h00	**SCHEERES**	Di Ruzza / Crespi	**BATYGIN**	Efroimsky / Hadden	Mogavero / Rekier
11h20		Legnaro / Griveaud		Georgakarakos / Daquin	Mastroianni / Zoppetti
11h40	**FABRYCKY**	Lari / Haghighipour	**LAI**	Christiaens / Gronchi	Todorović / Valente
12h00		Grassi / Pichierri		Suto / Hernandez	Hayashi / Coyette
	Observatory (5 min) LUNCH	LUNCH	LUNCH	LUNCH	LUNCH
14h00	Vavilov / Kumar	**JOHANSEN**	**BOLMONT**	**DORN**	**PETIT**
14h20	Benet / Rodriguez				
14h40	Lhotka / Pucacco	**Round-table**	**A few words by Anne**	**Round-table**	**RAMBAUX**
15h00	Ragozzine / Gomes	**Space Awareness**	Charalambous / Yseboodt	**Habitability**	
15h20	Pilat / Knežević		Revol / Saillenfest		
	COFFEE BREAK	COFFEE BREAK	Ghosh / Xi	COFFEE BREAK	COFFEE BREAK
					LEE
16h20	Dermott / Kokubo	Rossi / Courtot	COFFEE BREAK	**CORREIA**	
16h40	Sicardy / Mah	Tommei / Petit (Al)	Leleu		**LASKAR**
17h00		Torii / Romano	Korth	**BALAND**	
17h20		Li / Farhat	Baycroft		
17h40		Dogkas			
18h		Celletti			
	WELCOME RECEPTION 18h-20h BOAT TOUR		**VERA RUBIN SHOW** 20h	**GALA DINNER** 19h	
	OBSERVATORY		**OBSERVATORY**		

SMALL BODIES DYNAMICS	RESONANCES
SPACE DEBRIS	EXOPLANETS
ROTATION	LONG-TERM EVOLUTION & STABILITY
FORMATION	NUMERICAL METHODS

INVITED TALKS

The obliquity of Mercury: Models and interpretation, by Rose-Marie Baland[1]

[1] Royal Observatory of Belgium

Mercury is locked in an unusual 3:2 spin-orbit resonance and as such is expected to be in a state of equilibrium called Cassini state. In that state, the angle between the spin axis and orbit normal, called obliquity, remains almost constant while the spin axis remains almost in the plane, also called Cassini plane, defined by the normal to the Laplace plane and the normal to the orbital plane. The spin axis and the orbit normal precess together with a period of about 300 kyr. The orientation of the spin axis of Mercury has been estimated using different approaches: (i) Earth-based radar observations, (ii) Messenger images and altimeter data, and (iii) Messenger radio tracking data. The different estimates all tend to confirm that Mercury occupies the Cassini state. The observed obliquity is small and close to 2 arcmin. It indicates a normalized polar moment of inertia of about 0.34. This information, combined with the existence of a liquid iron core, as evidenced by the librations, allows to constrain the interior structure of Mercury. However, the different estimates of the orientation of the spin axis locate the spin axis somewhat behind or ahead of the Cassini plane, and it is difficult to reconcile and interpret them coherently in terms of detailed interior properties. We will review recent models for the obliquity and spin orientation of Mercury, which include the effects of complex orbital dynamics, tidal deformations and associated dissipation, and internal couplings related to the presence of fluid and solid cores. Next, we will discuss the possible interpretations of the orientation estimates in term of interior properties.

Towards a Unified Model of Planet Formation, by Konstantin Batygin[1]

[1] California Institute of Technology

Over the course of the last two decades, few astronomical discoveries have generated broader interest than the detection and characterization planetary systems that encircle other stars. The basic properties of the majority of these planets are different from those of our own solar system in a number of ways: extrasolar worlds have orbital periods that are measured in days rather than years; have masses that exceed the Earth by a factor of a few; appear to be silicate-rich though routinely possessing substantial Hydrogen-Helium atmospheres; and frequently occur in multiples. Beyond these basic attributes, recent work has revealed that short-period extrasolar planets exhibit an intriguing pattern of intra-system uniformity, which stands in sharp contrast with the staggering overall diversity of the Galactic Planetary Census. In this talk, I will discuss a new theoretical picture for rocky planet formation that satisfies the aforementioned constraints. Building upon recent work — which demonstrates that planetesimals can form rapidly at discrete locations in the disk — we propose that super-Earths originate inside rings of silicate-rich planetesimals at approximately 1 AU. Within the context of this picture, we show that planets grow primarily through pairwise collisions, until they achieve terminal masses that are regulated by isolation and orbital migration. Numerical simulations carried out within this theoretical framework produce synthetic planetary systems that bear a close resemblance to compact, multi-resonant progenitors of the observed population of short-period extrasolar planets. I will further discuss how this model fits into the broader context of the formation of the terrestrial planets of the solar system as well as the Galilean satellites.

Alternative state representations for orbit prediction, by Giulio Baù[1]

[1] University of Pisa

In the framework of the perturbed two-body problem, Cartesian coordinates of position and velocity are usually chosen for state representation. In some specific situations, like for example in the case of an asteroid having close encounters with a planet, more suitable coordinates can be used to achieve a higher accuracy in orbit prediction. In this talk I will give an overview of some sets of nonsingular variables connected to linearizations regularizations of the two-body equations of motion, with a particular focus on recent formulations whose definition relies on an "intermediate" reference frame. In the last part, I will introduce another set of variables, known as "generalized equinoctial orbital elements" and tell you about ongoing work on their application to build a new analytical theory of the so-called "main problem" of the artificial satellite.

A journey from planets to stars: improving tidal models in orbital evolution codes, by Emeline Bolmont[1]

[1] University of Geneva

Tides shape the architecture of most detected planetary systems. It impacts the rotation and orbit of planets, as well as the rotation of the star. Currently, most studies involving tides consider simple equilibrium tide models such as the constant time lag (e.g. Hut 1981) or constant phase lag (Goldreich & Soter, 1966). While being practical and valid for a subset of objects (i.e. made of weakly viscous fluids), these models cannot account for the complexity of the response of a rocky planet (e.g. Makarov & Efroimsky, 2013) and by definition do not account for the dynamical tide. A large number of the discovered planets are thought to be rocky (e.g. Fulton et al. 2017) and previous studies highlighted the importance of taking into account the dynamical tide in the convective zone of young stars for the survival of close-in hot Jupiters (e.g. Bolmont & Mathis 2016). This last aspect is particularly important as we are now starting to obtain measurements of the tidal dissipation inside stars (e.g. Yee et al. 2020; Vissapragada et al. 2022). For these reasons, it is fundamental to improve our tidally-induced orbital and rotational evolution models. I will give an overview of the different modeling efforts made in my team and the different codes that are being developed. We are working on two kinds of codes: 1) a secular code (ESPEM, Benbakoura et al. 2019) which solves equations for the semi-major axis, eccentricity and rotation rate of one planet orbiting a star (e.g. Boué & Efroimsky, 2019); 2) a N-body code (Posidonius, Blanco-Cuaresma & Bolmont 2017) which considers various different effects, including tides. In both cases, we implemented the Kaula formalism in a flexible way so that every type of planet/star can be considered provided the frequency dependence of the potential Love number of degree 2 is known. I will present an overview of some results we obtained with these codes. In particular, in Revol et al. (submitted), we use ESPEM to investigate the rotational evolution of a Venus-like planet with and without an atmosphere. In Revol et al. (in prep), we investigate with Posidonius the orbital and rotational evolution and the tidal heating of the TRAPPIST-1 planets. Finally, in Kwok et al. (in prep), we investigate the impact of the stellar dynamical tide on the orbital evolution of close-in planets taking into account the corresponding complex frequency dependence of the Love number (Ogilvie & Lin 2007; Astoul & Barker 2022).

New methods to study the tidal evolution of planetary systems, by Alexandre Correia [1]

[1]University of Coimbra

In this talk, we present new approaches to the model the tidal evolution of N-body systems. We compute the instantaneous deformation of extended bodies using a differential equation for the inertia tensor. This method can take into account a wide class of perturbations, including chaotic motions and transient events. We present a new open-source N-body code to handle the tidal evolution of planetary systems. We also derive the secular equations of motion in a vectorial formalism, which is frame independent and valid for any rheological model. We show that for viscoelastic rheologies, which are suitable for rocky planets, spin-orbit resonances arise naturally and can trigger high obliquity metastable states.

Planetary systems in resonant chains, by Jean-Baptiste Delisle[1]

[1] University of Geneva

Planetary systems in resonant chains are of particular interest both from a dynamical point of view and an observational point of view. In particular the three planet resonant angles are a valuable observable for transiting systems. Indeed, transit timing observations allow to measure the libration of these angles while in most cases the two planet angles cannot be observed. The final equilibrium of three planet angles (around which the system is observed to librate) depends on the formation and evolution of the system. For instance, it may depend on the order in which the planets were captured

in the chain. Therefore, observing a system around a specific equilibrium provides clues about its formation and evolution. Models of resonant chains can also be used (and have been used) to predict the periods and phases of additional planets in systems known to already harbor resonant planets. This is especially interesting to infer the orbit of planets for which a single transit was observed, and for which we cannot determine the period without further constraints. In this talk, I will present an analytical model of resonant chains and its application to several emblematic systems (Trappist-1, TOI-178, Kepler-223, etc.).
Refs.: https://ui.adsabs.harvard.edu/abs/2017AA...605A..96D/abstract
https://ui.adsabs.harvard.edu/abs/2021AA...649A..26L/abstract

Planet cores store majority of planetary water budgets, by Caroline Dorn[1]
[1] ETH Zurich
There is a lot of enthusiasm in the exoplanet community for the detection and characterization of super-Earth and sub-Neptunes. There is a lack of similar planets in the Solar System and therefore their origin and atmospheric evolution represent an important challenge for our understanding of planets. Moreover, the majority of current formation and evolution models suffer from simplified assumptions of chemically inert interiors and cold rocky interiors in solid-state, as well as the neglect of volatile-exchange at the rock-atmosphere interface. This prevailing view is shifting: (1) the majority of exoplanets are partly molten, i.e., they host global magma oceans; (2) redox reactions between magma and atmospheric volatiles affect bulk composition; and (3) magma oceans represent huge reservoirs for volatiles. The exoplanet community is just beginning to explore new dimensions of these deep volatile reservoirs in exoplanets and their influence on planet structure and evolution.

Resonant Chain Dynamics: Interpretation of Observations, by Daniel Fabrycky[1]
[1] University of Chicago
Resonant chains of exoplanets are systems in which 3 or more planets are librating in 3-body and likely two-body mean-motion resonances. By this definition, about 10 systems have been found so far, and approximately one new one per year are being added to the family; this talk will survey those observed systems. Among massive planets, 2:1 is the most likely resonance for pairs, but 3:2 and 4:3 are more common for sub-Neptune down to Earth-mass planets, which suggests embedded migration (type I) has torques stronger than the wider resonances. Meanwhile, additional planets are sometimes found not participating in the resonance, which also constrains the history of migration in the system. After the system has formed into a resonance, it can spread due to tidal damping in the planets. Constraining planetary tidal damping parameters is an exciting prospect, promising to tell us details of the planetary structure and material properties, beyond what we can learn from mass and radius. We will discuss some challenges some systems give to deriving those tidal constraints. We will also discuss how transit timing probes the libration of the resonances, further constraining migration and tidal damping histories.

Dynamics modelling and stability analysis of satellites orbiting oblate bodies, by Catalin Gales[1]
[1] Al. I. Cuza University of Iasi
The study of orbital evolution around an oblate object is capturing a renewed focus with the recent and forthcoming "in situ" explorations. The robotic missions, venturing towards minor bodies of the Solar system, have to face the unknown natural environment of the explored objects. A first evaluation of the environment can be inferred from the global dynamics analysis of the models describing the orbital motions, knowing or assuming some bounds for the physical parameters of the central body. On the other hand, post mission stability analysis can provide valuable information on the history and evolution of the system. This work discusses several techniques used for modelling the dynamics of satellites orbiting oblate objects, including a description of some models used for deriving the potential of the oblate body. Then, within the context of a perturbed two body problem, in which

the Keplerian motion of the small object is perturbed by the spherical harmonics of the central body, as well as the attraction of a third body (the Sun), the evolution of the orbital elements is analyzed, on various time scales, in terms of various parameters of the system. Finally, focusing on some specific cases, resonance effects are discussed and a global dynamics analysis is presented by using both analytical and numerical tools.

Destruction mechanisms for near-Earth objects, by Mikael Granvik[1,2]
[1] University of Helsinki
[2] Luleå University of Technology
For more than two decades the consensus in the community was that the majority of near-Earth objects (NEOs) are destroyed when they plunge into the Sun or collide with planets. In recent years, combining survey data with evolutionary models of the NEO population have revealed two additional destruction mechanisms of non-negligible importance: there is now strong evidence that NEOs are completely destroyed at short but nontrivial distances from the Sun as well as growing evidence that tidal forces produce an observable effect in the NEO orbit distribution as a result of very close planetary encounters. Whereas the susceptibility to tidal disruption primarily depends on an asteroid's interior structure, the susceptibility to destruction close to the Sun most likely depends on the bulk composition. Combining the dynamical and physical information of NEOs provided by ongoing and future observational surveys with an understanding of the destruction mechanisms can open up a new, probabilistic window into asteroid interiors. I will describe the evidence we have for both tidal disruptions and destructions close to the Sun as well as review ongoing observational, numerical, theoretical, and experimental work to understand in detail what causes the destruction of NEOs having perihelion distances shorter than the semimajor axis of Mercury.

Forming planetary systems via pebble accretion, by Anders Johansen[1]
[1] Globe Institute, University of Copenhagen
Nature displays a diverse set of planetary systems that contain gas giants, super-Earths and rocky planets in a variety of orbital configurations. I will demonstrate how such planetary systems are the natural outcome of planetary growth by accreting pebbles that drift through the protoplanetary disc. I will show that planetary migration provides a major force in shaping the planetary architectures for both small and large planets. Finally, I will present the ongoing debate about whether Earth formed rapidly by pebble accretion or slowly by consecutive giant impacts.

Hot Jupiters and Super-Earths: Spin-Orbit Puzzles in Exoplanetary Systems, by Dong Lai[1]
[1] Cornell University
I will discuss two topics on exoplanetary systems. The first concerns hot Jupiters, giant planets with orbital periods of a few days. Observations have revealed that many hot Jupiters have orbits that are highly misaligned with the rotation of their host stars. How did such large stellar obliquities come about? What do they inform about the formation of hot Jupiters? The second topic deals with planetary obliquity, which reflects the planet's dynamical history, and can strongly influence the atmosphere condition and climate of the planet. Many Sun-like stars are observed to host close-in super-Earths (or Earth-like planets) as part of a multi-planetary system. Can such super-Earths (or similar habitable planets around M stars) sustain significant obliquities?

Dynamics of Circumstellar Planets in Binary Star Systems, by Man Hoi Lee[1]
[1] The University of Hong Kong
Circumstellar planets in binary star systems provide unique constraints on the formation and dynamical evolution of planets. I will discuss HD 59686 and nu Octantis, which are the tightest binaries with circumstellar planets. For HD59686, dynamical fitting of the radial velocity data and stability analysis show that the planet must be either on nearly coplanar retrograde orbit or in one of the

narrow regions of prograde orbit stabilized by secular apsidal alignment. For nu Octantis, a nearly coplanar retrograde planetary orbit is the only option for dynamical stability, and we have explored the possibility that the secondary star of 0.57 solar mass is a white dwarf. I will also discuss the mysterious case of the highly eccentric (e = 0.93) binary epsilon Cygni. It shows short-period radial velocity variations that closely resemble the signal of a Jupiter-mass planet orbiting the primary star but the period and amplitude change over time and dynamical stability analysis rules out a planet.This work was supported in part by the Hong Kong RGC grant HKU 17306720.

Interdisciplinarity: an effective approach to comprehending the formation of planetary systems, by Alessandro Morbidelli[1]
[1] CNRS, Observatoire de la Côte d'Azur
The diversity of planetary systems and of planets within a given system reveals the complexity of the formation and evolution process, which is highly sensitive to the initial conditions and environmental factors. To tackle this complexity, various disciplines must work together synergistically. Since Newton, Mathematics has provided the necessary tools to comprehend the evolution of planetary systems, including their long-term stability (or instability) and their past evolution, such as capture in or passage through resonances. The partnership between Mathematics and Geophysics, which is integral to any radioscience experiment in space missions, provides the best method to uncover the interior structure of planetary bodies. Planets form or begin to form in protoplanetary disks of gas and dust, which are also susceptible to ionization and coupling with the ambient magnetic field, making Magneto-Hydrodynamics crucial to understanding the distribution of mass and its evolution, namely the initial conditions of planet formation, as well as planet-disk interactions. Lastly, Cosmochemistry provides the most stringent constraints on the formation of our Solar System, offering exquisite compositional and chronological data that leave little ambiguity in models. This non-exhaustive list of interdisciplinary approaches highlights the importance of breaking communication boundaries across fields.

Long-term stability of compact planetary systems, by Antoine Petit[1]
[1] Observatoire de la Côte d'Azur
Exoplanet transit surveys have revealed the existence of numerous multi-planetary systems packed close to their stability limit. The majority of these exoplanet systems lie in-between the main two-planet resonances. I will show how the dynamics governing the stability of such systems is dominated by the interactions between the resonances involving triplets of planets. The complex network of three-planet mean motion resonances drives a slow diffusion of the semi-major axes, that can lead to the destabilization of the system on short timescales. This process reproduces quantitatively the timescale of instability obtained numerically over several order of magnitude in time and planet-to-star mass ratios. As this dynamical process dominates the dynamical rearrangement of planetary systems at the end of their formation, we observe on the system's architecture signpost of these events.

Long-term evolution of exoplanet systems, by Cristobal Petrovich[1]
[1] Pontificia Universidad Catolica de Chile
In this talk, I will review some recent developments on the stability of multi-planet systems and the long-term evolution of systems affected by dynamical instabilities. I will highlight recent results tackling this complex subject using different approaches such as machine learning techniques to long-term orbit-averaged models that map out to a range of enigmatic exoplanet populations.

Lunar reference system from science to MoonLight and LunaNet, by Nicolas Rambaux[1]
[1] Sorbonne Université / IMCCE - Observatoire de Paris
The Lunar-laser ranging observations allow today to measure the rotation of the Moon, since 50 years thanks to Apollo missions and the precision is about the milli-arcsecond. This remarkable precision requires numerical dynamical models fitted to the observations such as the Intégration Numérique

Planétaire de l'Observatoire de Paris (INPOP) lunar ephemerides. In preparation to future missions, we will show how the study of dynamical models allows to extract information on the interior structure of the Moon and we also discuss the current definitions of the lunar coordinate systems. The precise definition of the lunar reference system will be useful for the cartographic systems of future space missions.

On the Multiscale Astrodynamics of Cislunar xGEO Space, by Aaron Jay Rosengren[1]
[1] University of California San Diego
The nonlinear astrodynamics in the cislunar space beyond the geosynchronous belt (xGEO), encompassing secular, resonant, chaotic, close-encounter, and manifold dynamics, is dramatically different than the weakly perturbed Keplerian approach used for over a half century for the detection and tracking of objects near Earth. In contrast to the traditional geocentric domains, the predominant resonances in xGEO are governed by octupolar and higher-order perturbations to the classical Kozai-Lidov-von Zeipel dynamics, among, hitherto, unstudied interactions with the lunar orbital and precession frequencies. Furthermore, while mean-motion resonances (MMRs) constitute one of the most important and far-reaching aspects of dynamical astronomy, they have remained woefully underrated in circumterrestrial dynamics, in part because the orbits of most satellites thus far are too low to be affected by mean-motion commensurabilities. Using detailed Hamiltonian-perturbation theory, grounded in astronomical insight and heritage, we uncover the nonlinear lunisolar secular resonances and lunar MMRs that significantly affect the structure of xGEO phase space. The orbital architecture of current and historic xGEO space objects differ markedly from the classical problems presented by nature (e.g., dominant forces, relevant timescales, hierarchical configurations, etc.), rendering many of the time-honored methods of Solar-System dynamics inapplicable. In this talk, we will showcase the inherent limitations of the perturbed two-body approach and highlight how the local picture can be complemented with the global geometric dynamical portrait provided by semi-analytical approaches to the restricted three-body problem. Aspects of this research have been done in collaboration with S. D. Ross (VT), R. Malhotra (LPL), N. Todorovic (AOB), and D. Wu (MIT).

Binary Asteroids: A Pathway to Understanding the Morphological Evolution of Rubble Pile Asteroids, by Daniel Scheeres[1]
[1] University of Colorado
Binary asteroids are found frequently within the small Near Earth Asteroid (NEA) population, with about 15be binaries. However, there are reasons to believe that the processes that create binary asteroids are the same that drive the overall evolution of small rubble pile asteroid morphologies. In this talk we will outline how the processes that create binary asteroids should shape many other aspects of the small asteroid population. Motivated by this, it becomes clear that the study of binary asteroids to determine the details of their formation processes may also provide insight and understanding on the overall evolution of the small body population in the solar system. We will introduce possible approaches to exploring binary asteroids that could further unveil the formation mechanics of these systems, and hence shed insight on the small body population.

TALKS

The BEBOP search for circumbinary planets in radial velocity, by Thomas Baycroft[1]
[1] University of Birmingham
The BEBOP (Binaries Escorted By Orbiting Planets) survey is a search for circumbinary planets using the radial velocity spectrographs Harps and Sophie, currently focussing on single-lined binaries with a mass ratio < 0.3. Circumbinary systems are an important testing ground for planet formation theories as the dynamically complex influence of the binary makes planet formation and survival more difficult. Obtaining a larger sample of such planets, along with accurate characterisation of these planets and occurrence rates is therefore vital to further our understanding. Recently, progress has been made to overcome/circumvent the observational difficulties that have been hampering circumbinary planet detection. For radial velocities, one such method is to observe single-lined binaries allowing us to bypass the entanglement of the two stellar spectra, the BEBOP survey has thus achieved sensitivity down to Saturn mass planets across a wide range of orbital periods for many of our targets. I will present the results of the survey so far including: confirmed planets such as BEBOP-1c the first circumbinary planet detected in radial velocity; our promising candidates; and the status of our observations.

Transversal Yarkovsky acceleration for Apophis exploiting automatic differentiation tools, by Luis Benet[1]
[1] Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México
We present an estimation of the Yarkovsky transversal parameter based on optical and radar astrometry for (99942) Apophis, which includes observations obtained during 2021 Apophis' fly-by, and a numerical approach which exploits automatic differentiation techniques. We find a non-zero Yarkovsky parameter, $A2 = (-2.899 \pm 0.025) \times 10^{-14}$ au d^{-2}, with induced semi-major axis drift of (-199.0 ± 1.5) m yr^{-1} for Apophis. Our results allow to estimate the collision probabilities for the close approaches in 2029, 2036 and 2068.
This is joint work with Jorge A. Pérez-Hernández.

SIMPRO: a simulator of breakup events and propagation of orbits of space debris, by Alessandra Celletti[1]
[1] University of Rome Tor Vergata
Motivated by the need to analyze the dynamics of space debris, we reconstructed a simulator based on the NASA/JSC break-up model EVOLVE 4.0. We describe the main features of the program, which simulates a break-up event with default or chosen values of the main parameters; the program also propagates the dynamics of the generated fragments, either using Cartesian or Hamiltonian frameworks, and it includes some statistical data analysis. The executable program SIMPRO will be soon available on-line.
This is a project in collaboration with Marius Apetrii, Christos Efthymiopoulos, Catalin Gales, and Tudor Vartolomei.

Tidal effects in resonant chains of close-in planets, by Carolina Charalambous[1]
[1] Pontificia Universidad Catolica
Transit-timing variation (TTV) is a powerful technique to infer the existence of previously undetected planets by measuring the non-periodicity of the transit times resulting from the gravitational perturbations from other planets. The TTVs also provide a way of inferring masses and eccentricities in multiple transiting systems, in particular for systems near MMRs which are subject to large TTV signals. The amplitude and period of the TTVs strongly depend on the distance to the exact commensurability and the eccentricities of the planets. These quantities are often shaped during the phase of planet-disc interactions and, to a greater extent, modified during the long-term evolution of the system. In particular, for close-in planets the tides raised by the host star provide a source of dissipation on very long timescales, placing the planets further away from the commensurabilities. In this work, we will discuss how the tidal interactions play an important role in shaping the period ratios in

planetary systems with resonant chains, highlighting that the trend observed in the resonance offsets are due to the 3-planet resonant dynamics. Moreover, we will show how the tidal interactions between the planets and the central star can impact the TTVs and therefore how the TTVs could serve as a means to put constraints on the tidal history of the planetary systems. The study will focus on the Kepler-80 system, which harbor a resonant chain of four close-in planets.
Authors: Carolina Charalambous, Anne-Sophie Libert

A new directly imaged giant planet, by Valentin Christiaens[1]
[1] Université de Liège
The discovery and analysis of the PDS 70 b and c protoplanets represents a significant leap forward in the gathering of observational constraints to the processes involved in giant planet formation. However our understanding of these processes is still far from complete. These first discoveries fuelled a number of new questions. Are these protoplanets outliers compared to the larger population of newborn giant planets? Or were we lucky to catch them at the most favourable moment of the combined planet+disk evolution to allow for a direct imaging discovery? How would have they looked like a few Myrs earlier? Unambiguous confirmation of other protoplanets is now required to place these discoveries in a broader context. In this contribution, I will present our recent confirmation of a new protoplanet candidate with direct imaging. We imaged this protoplanet in the wide annular gap separating the two main rings of a face-on disk. Its presence is confirmed in multiple epoch VLT/SPHERE observations and trace 4 years of Keplerian motion. Our new images also reveal a conspicuous outer spiral wake associated to the companion, consistent with predictions from hydrodynamical simulations. Both the detection in polarized intensity and the tentative NIR spectrum extracted for the protoplanet suggest it is enshrouded in a significant amount of dust, be it in the form of a circumplanetary disk or envelope. I will discuss additional follow-up observations that could fully validate this hypothesis and enable a better characterization of the object, as well as the implications for the direct imaging search of protoplanets.Giant planet formation is still poorly understood. The discovery and analysis of the PDS 70 b and c protoplanets represents a significant leap in the gathering of observational constraints to the process of giant planet formation. Are these protoplanets outliers compared to the larger population of newborn giant planets? Or were they caught at the most favourable moment of the combined planet+disk evolution to allow for a direct imaging discovery? How would have they looked like a few Myrs earlier? Unambiguous confirmation of other protoplanets is now required to place these discoveries in a broader context. In this contribution, I will present our recent confirmation of a protoplanet candidate with direct imaging. We imaged this protoplanet in the wide annular gap separating the two main rings of a face-on disk. Its presence is confirmed in multiple epoch VLT/SPHERE observations and trace 4 years of Keplerian motion. Our new images also reveal a conspicuous outer spiral wake associated to the companion, consistent with predictions from hydro-dynamical simulations. Both the detection in polarized intensity and the tentative NIR spectrum extracted for the protoplanet suggest it is enshrouded in a significant amount of dust, be it in the form of a circumplanetary disk or envelope. I will discuss additional follow-up observations that could fully validate this hypothesis, and enable a better characterization of the object.

Chaos in meteor showers: the example of Draconids, Leonids and Taurids, by Ariane Courtot[1]
[1] IMCCE, Observatoire de Paris
Meteoroids have peculiar dynamics owing to their relativly high non-gravitational forces and their multiple close encounters. They are ejected from a comet-like parent body, forming a stream. When a meteoroid stream meets with the Earth, a meteor shower is produced.Today more than 900 meteor showers are listed by the IAU, meaning a similarly large number of comet-like parent bodies existed in the Earth vicinity in the near past (1-100kyrs). This raises the question of the authenticity of these showers. To tackle this, we aim to better understand the dynamical evolution of meteoroids, which can be done by drawing chaos maps. We studied the Draconids and Leonids meteor showers, whose

orbits are close to respectively Jupiter-family comet and Halley-type comet. The effect of MMR with Jupiter will be sahown in both cases, as well as the effect of close encounters, mainly with Jupiter, Saturne and the Earth. A first exploration of the impact of non-gravitational forces will also be presented.Finally, we will present our first work on the Taurids, a group of meteors which are sometimes considered a meteor shower. We will use this last example to explain how our chaos maps can weight on the classification of this kind of meteor group.

Cassini States of Ganymede and Callisto, by Alexis Coyette[1]
[1] University of Namur
Like our Moon, the large icy satellites of Jupiter are thought to be in a Cassini State, an equilibrium rotation state characterized by a synchronous rotation rate and a precession rate of the rotation axis equal to that of the normal to the orbit. In these equilibrium states (up to four Cassini States are possible for a solid and rigid satellite), the spin axis of the satellite, the normal to its orbit and the normal to the inertial plane remain coplanar with an obliquity that remains theoretically constant. However, as the gravitational torque exerted on the satellite shows small periodic variations, the orientation of the rotation axis will also vary with time and nutations in obliquity will appear. Here we present the influence of the triaxiality and of the presence of a subsurface ocean on the Cassini States of Ganymede and Callisto and assess the possibility of determining whether a future observation of the obliquity of Ganymede or Callisto by the JUICE Mission could constrain the interior structure of these satellites.

Terrestrial Planet formation Simulations: Homogeneous Comparison between Methods, by Samuele Crespi[1]
[1] New York University Abu Dhabi
During the last phases of planet formation, the innermost part of planetary systems is populated by Moon- to Mars–size rocky objects called protoplanets. While the processes that lead to the formation of these objects are still under investigation, it is widely accepted that the subsequent mutual collisions among them play a key role in the final structure and composition of the planetary system.Due to the vast range of masses and velocity involved, the outcome of these collisions can vary considerably from perfect merging to the catastrophic destruction of the two colliding embryos. During the collision, a fraction of the total mass involved can be ejected in the form of debris, in particular volatile materials like water. It has been shown in different works that a significant part (up to 30%) of the cumulative mass of planetary embryos is converted into collisional debris.While planetary collisions are well described by state-of-the-art SPH simulations, the problem of including collisional debris in N-body simulators is far from being solved. Several solutions have been proposed, the most sophisticated of which incorporates the possibility of adding collisional debris to the simulation by clustering it into a few new bodies. However, in order to keep the total number of bodies in the simulation reasonably small, these new bodies are all generated with the same mass, usually of the order of one lunar mass.Another possible approach is to consider the debris as unresolved material distributed in circular bins. Although this second method is capable of better describing the statistical effect of small debris, the orbits of the unresolved material have been assumed to be circular and coplanar, and to be confined into bins of fixed width (0.1 or 0.4AU). However, recent studies on the statistical properties of collisional debris have shown that the mass and orbital distributions of this material can play a significant role in the orbital and chemical evolution of terrestrial planets.Here we present the results of our work in which we performed a homogeneous comparative test between the 4 commonly used methods to include collisions in simulations of terrestrial planets formation. To do so we performed a total of 80 N-body simulations, 20 per method, in which the collision outcome is retrieved by interpolating a dedicated dataset of SPH simulations. We show how and to which extent the simulation outcome, in particular the mass and composition of the formed planets, is affected by the method chosen to incorporate post-collisional debris in the simulation.

Quantifying chaos with geometrical indicators, by Jérôme Daquin[1]

[1] University of Namur
This contribution reports on new global dynamics and non-variational tools able to discriminate between ordered and chaotic motions. The methods are based on geometrical properties of orbits (such as lengths and stretches), are free of variational equations and are valid for discrete and continuous models. We demonstrate the ability of the proposed indicators to portray chaos on a series of problems relevant for astrodynamical and celestial problems.

Asteroid family membership in the inner belt, by Stanley Dermott

Most asteroids are not primordial bodies, but the products of cratering events and catastrophic collisions that resulted in the formation of a small number of asteroid families. In the inner main belt (IMB), about half the asteroids with absolute magnitudes, $H < 16.5$ belong to about 6 major families. Membership of these families is currently determined using the Hierarchical Clustering Method (HCM) which specifies that each member of a given family has an orbit that is separated from the orbit of its nearest neighbor by a distance less than some critical distance. This critical distance is, to some extent, arbitrary and while a further quarter of the asteroids in the IMB probably reside in the halos of the same 6 major families, these halo asteroids cannot be attached unambiguously, using the HCM alone, to a specific family. In addition to the halo asteroids, a further one quarter of the IMB asteroids are currently classified as non-family. We argue here that the lack of a reliable method of determining family membership is a major obstacle to understanding the dynamical evolution of the asteroid belt. Recognizing that the HCM leaves half the asteroids in the IMB unclassified, here we explore other methods of determining family membership. These methods supplement the use of the orbit separations with observations of the distributions of the asteroid orbital elements, albedos, colors, spin directions and size-frequency distributions.
Authors: Stanley F. Dermott, Dan Li and Apostolos A. Christou

Analysis of co-orbital motion of real asteroid in a medium-term timescale, by Sara Di Ruzza[1]
[1] University of Palermo
The focus of this work is the current distribution of asteroids in co-orbital motion with Venus, Earth and Jupiter, under a quasi-coplanar configuration and for a medium-term timescale of the order of 900 years. A co-orbital trajectory is a heliocentric orbit trapped in a 1:1 mean-motion resonance with a given planet. The averaged planar circular restricted three-body problem is used as a tool to classify co-orbital dynamics, which can be quasi-satellite (QS), horseshoe (HS), tadpole (TP), according to the dynamical behavior. Transitions between different types of motion are analyzed as well as compound motions, which represent a coexistence of two dynamical regimes. The results provide a general catalog of co-orbital asteroids in the solar system, the first one to our knowledge, and an efficient mean to study transitions. We would also present the possibility to validate our study by means of the use of Artificial Intelligence.
Joint work with Elisa Maria Alessi, Andrea Barucci, Giulia Ciacci, Alexander Pousse.

Secular evolution of debris in highly eccentric and inclined orbits, by Anargyros Dogkas[1]
University of Rome Tor Vergata
The motion of a test particle around an oblate Earth with external perturbations because of the Moon, Sun, and other non-gravitational phenomena is a very well-studied subject. Nonetheless, most of the existing studies approximate the system considering small eccentricities and inclinations, which is not always the case. Using the second-order averaged Kaula expansion, for the Earth, and the Kaufman-Dasenbrock expansion, for the Moon and Sun, we extend the study of the secular evolution in the full domain of initial eccentricities and inclinations and we produce time-efficient codes for the simulation of the secular dynamics. We use this method to derive the proper elements for arbitrary initial eccentricity, generalizing previous works. Furthermore, we study the effects of non-gravitational

dissipative phenomena, namely the effects of atmospheric drag, which are relevant for highly eccentric orbits. We simulate the secular evolution under these effects and we discuss several interesting phenomena that arise from their interaction with resonances.

Pathways of Survival of Exomoons and Inner Exoplanets, by Michael Efroimsky[1]

[1] US Naval Observatory, Washington DC

It is conceivable that a few thousand confirmed exoplanets initially harboured satellites similar to the moons of the Solar system or larger. Could some of them have survived over the æons of dynamical evolution to the present day? The dynamical conditions are harsh for exomoons in such systems because of the greater influence of the host star and of the tidal torque it exerts on the planet. We investigate the stability niches of exomoons around hundreds innermost exoplanets for which the needed parameters are known today, and we determine the conditions of these moons' long-term survival. General lower and upper bounds on the exomoon survival niches are derived for orbital separations, periods, and masses.The fate of an exomoon residing in a stability niche depends on the initial relative rate of the planet's rotation and on the ability of the moon to synchronise the planet by overpowering the tidal action from the star. State of the art models of tidal dissipation and secular orbital evolution are applied to a large sample of known exoplanet systems with their estimated physical parameters.We show that in some plausible scenarios, exomoons can prevent close exoplanets from spiraling into their host stars, thus extending these planets' lifetimes. This is achieved when exomoons synchronise the rotation of their parent planets, overpowering the tidal action from the stars.Massive moons are more likely to survive and to maintain a high rotation rate of their host planets (higher than these planets' mean motion).
Authors: Valeri V. Makarov and Michael Efroimsky

The Impact of Laplace Surface Dynamics on Debris Disc Architecture, by Mohammad Farhat[1]

[1] IMCCE, Paris Observatory

Laplace was first to appreciate how the orbital architecture of Jupiter's satellites is shaped by the combined gravitational perturbations of Jupiter's bulge, and the Sun. As it happens, the influence of the two perturbers can balance on stationary orbits, the so called Laplace equilibria, which align with the planet's equator on the inside then smoothly approach the planet's orbital plane on the outside. Thus emerges the Laplace Surface, dynamics around which captures the motion of test particles (e.g. satellites, planetary rings, debris planetesimals, planets) in the presence of hierarchical inner and outer perturbers, both at home and abroad. In this talk, we revisit this classical dynamical regime, generalizing Laplace's framework to allow for a fairly eccentric and sufficiently inclined massive outer perturber. We shall highlight key novel results, and draw their implications focusing specifically on the structure of the extrasolar HD 106906 system. This interesting system harbors a low-mass disc that is forced from the inside by a stellar binary, and from the outside by a directly imaged wide, eccentric, and inclined planetary companion. We depict how living around the Laplace surface imposes a dynamical break at the disc's location, resulting in distinctive observational signatures which we render via simulated surface density/brightness maps and vertical structure profiles. Our exploration within the secular dynamical framework maps the disc's morphological features (e.g., asymmetries, warps) as a function of the outer planet's orbit, with and without radiation pressure. We use this mapping to constrain the wide uncertainties on the planet's orbit; but more importantly, to ease the tension of the disc's observed morphological discrepancies between millimeter imaging (via ALMA) and scattered light imaging (in HST then polarimetric observations). We finalize by discussing the phase space structure, arguing that initially cold discs are destined to evolve on a robust structure, specifically a separatrix, which carries debris planetesimals on excursions of inclination and eccentricity. This phase space structure establishes the relevance of our results to a variety of hierarchical systems, as we set the stage for generalizations that allow for disc self-gravity and collisional evolution.

Dynamical habitable zones for circumbinary planets, by Nikolaos Georgakarakos[1]

[1] New York University Abu Dhabi

Determining habitable zones in binary star systems can be a challenging task due to the evolution of planetary orbits and varying stellar irradiation conditions. 'Dynamically informed habitable zones', however, allows us to make predictions on where to look for potentially habitable planets in such complex environments. That type of habitable zone has been used in the past to investigate the habitability of circumstellar planets in binary systems or planets in systems that also hosted giant planets. In this work, the method is extended to planets on circumbinary orbits. The method is applied to some of the circumbinary systems discovered by the Kepler and TESS missions. Many of those systems are found to be suitable for potentially hosting terrestrial planets that can retain liquid water on their surfaces.

Dynamical Instabilities and the Orbits of Kepler's Multis, by Tuhin Ghosh[1]

[1] Tata Institute of Fundamental Research

Discovered high multiplicity exoplanet systems are generally more tightly packed when compared to the solar system. Such compact multi-planet systems are often susceptible to dynamical instability. We investigate the impact of dynamical instability on the final orbital architectures of multi-planet systems using N-body simulations. Our models initially consist of eight planets placed randomly according to a power law distribution of mutual Hill separations. We find that more than 90dynamical instability, losing at least one planet. The surviving systems emerging from this chaotic evolution closely resemble the Kepler-detected multi-planet systems in terms of distributions of planetary masses, orbital periods, period ratios, and mutual Hill separations after taking into account transit geometry and Kepler detection efficiency. Our simulations reproduce various trends among observed Kepler planets, such as multiplicity-dependent eccentricity distribution, smaller eccentricities for larger planets, and intra-systems uniformity. These findings indicate that dynamical instabilities may have played a vital role in the final assembly of super-Earths and sub-Neptunes.

The passage through the 5:3 resonance between Ariel and Umbriel with inclination, by Sérgio Gomes[1]

[1] CFisUC

Ariel and Umbriel have almost certainly passed through the 5:3 mean motion resonance in the past owing to the tidal evolution of their orbits. However, the exact mechanism that allows the system to evade capture in this resonance is a great puzzle. For coplanar orbits (zero inclinations), the eccentricity of at least one satellite must be close to 0.01 at the time, which is unlikely because tides are expected to quickly damp the eccentricities to near zero. For non coplanar orbits, the inclinations appear to grow to high values, which is unlikely because tides are very inefficient to damp the inclinations to the presently observed near zero values. Assuming circular orbits for both satellites, we show that, if the inclination of Umbriel was higher than 0.1^{o} at the time of the resonance encounter, capture in the 5:3 mean motion resonance can be avoided. Moreover, after the resonance crossing, the inclination of Umbriel drops to a mean value around the presently observed one.

Revisiting the computation of the critical points of the squared distance between two ellipses with a common focus, by Clara Grassi[1]

[1] University of Pisa

Computing the critical points of the squared distance between two ellipses with a common focus is of great interest in Celestial Mechanics, in particular in relation to the computation of the MOID (minimum orbit intersection distance), that is the distance between the two ellipses. This is useful in various applications, from impact monitoring of near-Earth asteroids to the detection of conjunctions between space debris. Different methods to compute all the critical points have been developed, for example in Sitarski (1968), Kholshevnikov and Vassiliev (1999), Gronchi (2002). Starting from the expression of the squared distance in terms of the true or the eccentric anomalies of the two objects, we develop new methods, or revisit known ones, using the resultant theory. In each case, we obtain systems of two either ordinary or trigonometric bivariate polynomials and then apply the resultant theory to look for solutions. With one of the methods we are able to obtain the same trigonometric polynomial introduced in Kholshevnikov and Vassiliev (1999), using the resultant theory instead of Groebner's basis theory. For the different methods, we also test the reliability of the computed solutions using the results of Gronchi and Valsecchi (2013) on the maximum MOID and those of Gronchi and Niederman (2020) on the nodal distance. Finally, we provide a comparison of the accuracy of each method and discuss the computational efficiency.

Migration of giant planets in low viscosity discs and consequences on the Nice model, by Philippine Griveaud[1]

[1] Observatoire de la Cote d'Azur

It has recently been shown observationally and theoretically that proto-planetary discs are probably much less viscous than previously thought. In such discs, the migration of pairs of giant planets differs from the classical viscous case. In fact, using 2D hydrodynamical simulations with an α viscosity parameter of 10^{-4}, we have shown that Jupiter and Saturn get locked in the 2:1 mean motion resonance (MMR) and have a slow inward migration (see Griveaud et al. subm. and EPSC 2022). We conclude that in such low viscous discs the scenario of the Grand-Tack , in which Jupiter migrates inwards then outwards after being caught in the 3:2 MMR with Saturn is not possible. Another important scenario in the formation history of our system is the Nice Model, which takes place after the gas disc phase and assumes that the four (potentially five) giant planets ended their migration in a compact resonant chain. Once the gas was dissipated, an instability triggered by the crossing of those resonances brought the giant planets to their current orbits. This instability also explains many dynamical features in the Solar System (structure of the Kuiper Belt, distribution of Jupiter's trojan asteroids, irregular sateliltes of the giant planets, etc...) However, most studies of the Nice Model considered Jupiter and Saturn in the 3:2 MMR. A few recent studies have shown that this scenario could be possible with Jupiter and Saturn in the 2:1 MMR. We are also interested in investigating how the migration of giant planets in low viscosity discs may affect the initial conditions of this model. Adding Uranus, Neptune, and a potential 5th planet in our original simulations, we find the different possible resonant chains induced by migration. Generically, low viscosity discs favor large chains and low order resonances. We then let the disc evolve until the gas phase dissipates and study the dynamical stability of the system. We will present studies of the outcome of Nice-model-like global instabilities starting from resonant configurations arising from low viscosity discs, and compare these with the classical Nice model.

Initial orbit determination from one position vector and a very short arc of optical observations, by Giovanni Federico Gronchi[1]

[1] Universita' di Pisa

We address the problem of computing an asteroid orbit (OD problem) from one topocentric position vector $\mathcal{P}_1 = (\rho_1, \alpha_1, \delta_1)$, where ρ_1, α_1 and δ_1 denote respectively the topocentric distance, the right ascension and the declination at epoch t_1, and a very short arc (VSA) of optical observations, giving an attributable $\mathcal{A}_2 = (\alpha_2, \delta_2, \dot\alpha_2, \dot\delta_2)$ at the mean epoch $\bar t_2$ of the VSA. Using the algebraic conservation laws of the angular momentum, the Laplace-Lenz vector and the energy in the two-body dynamics, we can write the OD problem as a system of polynomial equations in the unknowns $\dot\rho_1$,$\dot\alpha_1$,$\dot\delta_1$,ρ_2, $\dot\rho_2$,z_2, where z_2 is an auxiliary variable.We prove that the system is consistent (i.e. it generically admits solutions, at least in the complex field), and we can obtain a univariate polynomial $\mathfrak{u}$ of degree eight in the unknown range ρ_2 at epoch $\bar t_2$ to solve the OD problem. Through a symbolic manipulator, we are also able to show that the degree of $\mathfrak{u}$ is minimum among the degrees of all the univariate polynomials in ρ_2 solving this problem.

This is a joint work with E. Scantamburlo and G. Baù

Celestial Mechanics with the celmech code, by Sam Hadden[1]

[1] CITA
I will introduce “celmech”, a new publicly available open-source python package for performing celestial mechanics calculations by constructing, manipulating, and integrating perturbative models for planetary systems’ dynamics. While direct numerical integrations with modern computers have largely replaced the need for highly precise perturbative calculations, classical perturbation theory still plays an important role in modern planetary dynamics by providing simplified models for a variety of complex phenomena including mean motion resonances, secular evolution, and dynamical chaos. Classical perturbation theories in planetary dynamics can be elegantly formulated using a Hamiltonian framework, but non-experts (and experts alike) can quickly get mired in the complexities of computing disturbing function expansions and Laplace coefficients. The celmech code automatically computes and evaluates disturbing function coefficients, allowing users to quickly and easily construct Hamiltonian models by adding disturbing function terms with any desired cosine arguments. The code also interfaces closely with the popular REBOUND N-body integrator so that users can easily compare perturbative models against direct N-body integrations. I will give an overview of the code and highlight some example applications. The code can be downloaded at github.com/shadden/celmech.

Secular Resonances and Terrestrial Planet Formation in Planetary Systems with Multiple Stars: Theory and Application, by Nader Haghighipour[1]
[1] University of Hawaii-Manoa
It has been known that the secular resonances of Jupiter and Saturn play crucial roles in the orbital dynamics of the inner solar system and structure of the asteroid belt. It has also been demonstrated that these resonances are fundamental to the formation of terrestrial planets and their internal composition (Haghighipour and Winter, 2016, CMDA, 124, 235). The discovery of giant planets in binary stars with separations smaller than 40 AU where the planet rotates around one of the stars of the binary motivated us to study secular resonances in these systems and investigate their effects on the formation of terrestrial planets. Using the concept of generalized disturbing function, we have developed a general theory for secular resonances in planetary systems with multiple stars and multiple planets. We have also carried out extensive simulations of terrestrial planet formation in moderately close binary star systems for different values of the binary separation, eccentricity, and mass-ratio as well as the number of giant planets. Results of the simulations are in perfect agreement with the theory and clearly demonstrate the effect of secular resonances. For instance, as the combined perturbation of giant planets and that of the secondary star causes the protoplanetary disk to lose material, secular resonances sweep across the disk, scattering more material out of the planet-forming region. As a result, planet formation is confined to a small region or in some instances is hindered completely. In systems where terrestrial planet formation proceeds constructively, the internal composition of the final planets are strongly influenced by the secular resonances as well. As expected, the rate of resonance sweeping varies based on the masses of the planets, the mass-ratio of the binary, and the instantaneous mass of the disk. We present the theory of secular resonances in planetary system with multiple stars, and discuss their effects in more detail. We also present implications of results of our simulation for the detection of terrestrial planets in binary star systems.

Lagrange stability of triple systems: disruption timescale distribution and its dependence on the orbital parameters, by Toshinori Hayashi[1]
[1] The University of Tokyo
The stability of triple systems is a long-standing problem in celestial mechanics, and there have been many studies and criteria proposed to predict the orbital stability/instability of triples. Nevertheless, these criteria are mostly based on the Lyapunov-type stability, which evaluates the local chaotic behavior to predict the stability/instability of triples. Although the Lyapunov-type stability is a mathematically well-defined concept, it is not directly related to the disruption of the systems. On the other hand, the Lagrange stability evaluates the stability/instability based on whether a triple is disrupted into a binary and an ejected single body. Therefore, it is physically more relevant for the

survival of a system and should be applied to a wide variety of situations in astrophysics, such as the possible presence of compact triples. To study the Lagrange stability, it is practical to consider the disruption timescales of triples with a variety of orbital configurations. We perform a series of direct three-body simulations and study the disruption timescale distribution, and its dependence on the initial orbital parameters. The result implies that the initial mutual inclination significantly affects the disruption timescale, and the Lyapunov-type stability does not always guarantee a long-term Lagrange stability especially for inclined triples. We discuss a possible physical origin of mutual inclination dependence by considering the orbital Energy transfer and the von Zeipel-Kozai-Lidov (ZKL) oscillations. In addition, the general relativistic (GR) corrections affect the stability and evolution of triples. The GR precession can suppress the strong ZKL oscillations, and the gravitational wave emissions shrink the orbital separation and trigger close binary mergers. We also discuss these effects and outcomes together with purely Newtonian case.

Switching integrators reversibly in the astrophysical N-body problem, by David Hernandez[1]
[1] Yale University
We present a simple algorithm to switch between N-body time integrators in a reversible way. We apply it to planetary systems undergoing arbitrarily close encounters and highly eccentric orbits, but the potential applications are broader. Upgrading an ordinary non-reversible switching integrator to a reversible one is straightforward and introduces no appreciable computational burden in our tests. Our method checks if the integrator during the time step violates a time-symmetric selection condition and redoes the step if necessary. In our experiments a few percent of steps would have violated the condition without our corrections. By eliminating them the algorithm avoids long-term error accumulation, of several orders magnitude in some cases.

Secular resonance maps, by Zoran Knežević[1]
[1] Serbian Academy of Sciences and Arts
We present the secular resonance maps in the phase spaces of proper elements and of secular frequencies for resonances due to terms up to degree 6 (8) in eccentricity and (sine of) inclination appearing in the perturbation theory. The resonant combinations of the rates of asteroid perihelia and nodes (g,s) and the corresponding fundamental frequencies of planets involving up to 4 frequencies were taken over from the previous work, while for these with 6 or 8 frequencies a systematically derived comprehensive lists are given here for the first time. There are 28 divisors in the theory of degree up to 4, 27 of which can give rise to resonances, while at the degree 6 there are (at least) 33 such resonant frequency combinations. The incomplete list of divisors with 8 frequencies includes 31 combinations.By plotting the resonant lines against the background of known asteroids, we straightforwardly determine resonances cutting the asteroid belt, thus possibly causing large long periodic variations of asteroid orbital elements, resonances located outside the region occupied by asteroids, hence not affecting their motion, resonances that interact with known families, those that bound the dynamically distinct regions, deplete or disturb asteroids in these regions etc.

Orbital Architecture of Planetary Systems Formed by Gravitational Scattering and Collisions, by Eiichiro Kokubo[1]
[1] National Astronomical Observatory of Japan
In the standard model of solar system formation, terrestrial planets are spontaneously formed by giant impacts of protoplanets or planetary embryos after the dispersal of protoplanetary disk gas. Similar models are also proposed for the formation of close-in super-Earths mainly discovered by the Kepler transit observations. In the giant impact stage protoplanets collide with each other to complete planets. We investigate the orbital architecture of planetary systems formed from protoplanet systems by giant impacts using N-body simulations. We systematically change the system parameters of initial protoplanet systems such as the total mass, mean semimajor axis, and dispersions of eccentricity and inclination, and investigate their effects on planetary systems. As system orbital architecture param-

eters we calculate the mean orbital separation of two adjacent planets and the orbital eccentricity of planets in a planetary system. We find that the orbital separation and eccentricity normalized by the Hill radius are nearly independent of the total mass, mass distribution, orbital separation, and eccentricity of the initial protoplanet systems in the realistic parameter range. On the other hand, they show a positive dependence on the mean semimajor axis and the bulk density of planets. This dependence can be explained by the equilibrium random eccentricity in this stage. If the system evolves by gravitational scattering and collisional coalescence, the equilibrium eccentricity is about the value of the two-body surface escape velocity normalized by the Keplerian velocity, which increases with the semimajor axis and bulk density of planets. We show that the orbital architecture is scaled by the equilibrium random eccentricity that includes the Hill scaling.

Hot Jupiters and their nearby surroundings, by Judith Korth[1]
[1] Division of Astrophysics, Department of Physics, Lund Observatory, Lund University
The first extrasolar planet, a so-called hot Jupiter (a gas giant planet with an orbital period of smaller than 10 days), forever changed our view of the Universe and our place in it. Still, after almost 30 years, it is not fully resolved whether hot Jupiters formed beyond the ice line and migrated inwards or in situ. Moreover, a type of system that was believed to not exists has been more often detected in the last years by TESS: a hot Jupiter accompanied by an inner low-mass planet. Furthermore, some of these systems are in a special orbit configuration where the orbital periods are close to a period commensurability and thus, show transit timing variations. We will present an insight into these rare systems that challenge the formation theories by showing our latest results from our photometric and radial velocity follow-up effort.

Europa-Induced Overlapping of Secondary Resonances in the 4:3 Jupiter-Ganymede Unstable Resonant Orbit Family, by Bhanu Kumar[1]
[1] Jet Propulsion Laboratory (JPL), California Institute of Technology
The phenomenon of mean-motion resonance overlapping is known to be crucial for the generation of large-scale instability in celestial systems, and is useful for low-energy space mission trajectory design. However, in most prior work, the model used is the planar CRTBP (PCRTBP), which takes only the gravitation of one moon into account. However, when designing tours of multi-moon systems, it is necessary to transition between resonances contained in regions of the phase space which are significantly affected by the gravity of two moons. Thus, at least a restricted 4-body model is needed to study these trajectories accurately; one such model is the concentric circular restricted 4-body problem (CCR4BP), where a third large body m_3 is added to the PCRTBP.In this work, we investigate the Jupiter-Ganymede unstable 4:3 interior resonant orbits in the CCR4BP. In the PCRTBP, where Europa's mass is neglected, this is a one-parameter family of unstable periodic orbits, where the parameter can be thought of as eccentricity or as unstable Floquet multiplier (higher eccentricity corresponds to the more unstable orbits). This PCRTBP periodic orbit family extends to eccentricities high enough to cause collision with Ganymede, with unstable multiplier going to infinity. However, in our previous work, attempts to numerically continue the higher eccentricity unstable PCRTBP periodic orbits by m_3 into the CCR4BP (where they correspond to tori) stopped before m_3 reached Europa's physical mass value m_E; in fact, the highest unstable multiplier whose orbit was successfully continued to the physical system was only 2.458 (under a stroboscopic map on the revolution of m_3). We seek to give a dynamical explanation for this continuation stoppage. After noticing pendulum-shaped gaps which appear among even the successfully continued, lower eccentricity Jupiter-Ganymede 4:3 resonant CCR4BP tori, we first track the size of the 4:3 torus parameterization Sobolev norms as a function of m_3 during the PCRTBP to CCR4BP continuation. We found that the norm blows up towards infinity at the m_3 value where continuation stops, which is a known indicator of torus breakdown. Thus, we take the portion of the 4:3 Jupiter-Ganymede torus family with stroboscopic map rotation numbers between 2.0349 and 2.0405, and continue a finely spaced mesh of these orbits by m_3, using very small steps ($\sim m_E/250$). We found that even

for $m_3 \approx m_E/4$, a very wide pendulum shaped gap centered at rotation number $2\pi\ 12/37 = 2.0378$ appears among the remaining tori, as well as less wide but still significant gaps centered at rotation numbers $2\pi\ 23/71 = 2.0354$ and $2\pi\ 25/77 = 2.0400$. These rational rotation numbers correspond to secondary resonances between the synodic frequency of Europa and the original PCRTBP periodic orbits' periods. Furthermore, as we increase m_3 to $2m_E/5$, the tori separating these three secondary resonances decrease in number and then disappear, indicating that these secondary resonances overlap in the physical Jupiter-Europa-Ganymede CCR4BP. Future unstable resonant orbit investigations in this phase space region for the Jupiter-Europa-Ganymede system should thus focus on computing periodic orbits, librational tori, and separatrices contained within secondary resonances.

Orbital evolution of the Galilean moons driven by a fast orbital expansion of Callisto, by Giacomo Lari[1]
[1] University of Pisa
The recent measure of the fast orbital migration of the Saturn's moon Titan opens new scenarios for the dynamical evolution of satellites' systems. More precisely, very-large tidal dissipation limited only at certain frequencies can result in a high migration rate also for outer satellites. In this context, the orbital history of the Galilean satellites of Jupiter could be very different from what expected by previous studies. In fact, so far, the three inner moons (Io, Europa and Ganymede) have been thought to have shaped the system's evolution through the combination of resonant and dissipative effects. However, similarly to what found for Titan, Callisto could have experienced a phase of very-fast orbital expansion, which would have strongly affected the evolution of all four moons. In this case, Callisto would have driven the system through divergent resonant crossings and temporary captures in a four-body resonant chain, that could have pumped the satellites' eccentricities. After that Callisto eventually escaped from the resonant chain, in few simulations we find that the system manages to reach its current configuration. Therefore, it is possible, although challenging, to build a self-consistent picture of the past history of the Galilean satellites for a fast migration of Callisto.

The AstroGeo project, by Jacques Laskar[1]
[1] IMCCE, Observatoire de Paris

MEO Secular Resonances: Phase Space, Eccentricity Growth and Diffusion of Navigation Satellites, by Edoardo Legnaro[1]
[1] Aristotle University of Thessaloniki
The presentation focuses on the role of inclination-only dependent lunisolar resonances in the dynamics of a MEO (Medium Earth Orbit) object over secular time scales (i.e. several decades). In particular, the focus will be the resonance's role in the "eccentricity growth" phenomenon. In fact, the effect of a lunisolar resonance is to increase an object's eccentricity, possibly up to a value where the orbit's perigee meets the earth's atmosphere. In this way, our results provide a framework useful to understand which initial conditions will lead to the re-entry of a MEO object. This allows for designing low-cost end-of-life disposal strategies for navigation satellites and mitigation procedures for space debris. In addition, results on the diffusion rates along such resonances will be presented.

Recovery and characterisation of resonant terrestrial planets hidden in transit surveys, by Adrien Leleu[1]
[1] Université de Genève
The bulk of compact multi-planetary systems we know to date have been detected by photometric surveys such as the missions Kepler, TESS, and the upcoming PLATO. For these systems, planet-planet gravitational interactions induce Transit Timing Variations (TTVs). When observable, TTVs allow us to put constraints on the masses and resonant state of observed multi-planetary systems, as well as discover new planets. However, TTVs are not always easily quantifiable. The use of non-adapted methods can lead to erroneous TTVs measurements, which in turn bias the estimated masses and

resonant state of the systems. In some cases, it can also lead to the non-detection of planets. These biases are stronger for smaller planets with large TTVs, typically terrestrial planets near or inside two-body mean-motion resonances (MMRs). It hence potentially impacts several major statistical results of the 2010s, notably the apparent paucity of exoplanetary systems inside MMRs, and the apparent low density of TTV-characterised planets. After describing these issues, I will introduce the RIVERS method. It consists of a preliminary analysis of the data using pattern-recognition machine learning, followed by a more traditional photo-dynamical analysis of the light curve. I will illustrate the method by showing the recovery of three pairs of resonant terrestrial planets that have been hiding in the data of the Kepler mission for over a decade. We will also see that the approach can facilitate the recovery of TTVs terms beyond the main TTVs frequency, allowing to break the mass-eccentricity degeneracy that usually prevents the obtention of robust masses for planets that are nearly resonant. Finally, I will discuss the broader implication of the results regarding the demographics of exoplanets and the study of resonant systems.

On the Celestial Dynamics of Charged Dust in the Solar System, by Christoph Lhotka[1]
[1] University of Rome Tor Vergata
We report on the recent progress in the field of charged dust dynamics in the solar system (1-4). Micron-sized dust in the interplanetary medium is continuously charged by photons and the solar wind (see, e.g. 5), leading to orbital perturbations caused by the Lorentz force effect due to its interaction with the interplanetary magnetic field. This force primarily results in latitudinal oscillations of the charged dust's orbital planes, but also affects other orbital elements on secular timescales. Using averaging theory, we examine this effect in depth and provide analytic estimates of oscillation periods and amplitudes, confirmed by numerical simulations of the unaveraged equations of motion. Our findings are based on simplified models of the interplanetary magnetic field but also apply to generalizations of the Parker spiral model, including time-dependent effects (such as the solar cycle) and the positive tilt angle between the sun's magnetic and rotation axis. Our orbital studies encompass particle dynamics inside and outside mean motion resonances with the planets, with a special focus on co-orbital motion with the planets Venus and Jupiter. The results of our study have implications for planetary formation theories during the planetary disk phase, as well as for the design of predictive mathematical models of space weather events, which are crucial in the planning of present and future interplanetary space missions.
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An overview of the high-inclination resonant population in the Kuiper belt, by Jian Li[1]
[1] Nanjing University
In this talk, we will provide a panoramic view of the dynamics of the Kuiper belt objects (KBOs) in the mean-motion resonances from the 1st-order to the 6th-order. With special emphasis on the KBOs' high inclinations up to 90 degrees, a series of new features appear: (1) starting from the 1st-order 2:3 resonance, we first define the SPECIL and GENERAL libration centres of the resonant angle, while these two centres are the same at zero inclination. Subsequently, we reveal the correlation of resonant amplitude with inclination, which is very important to determine the stability of resonant KBOs; (2)

for the asymmetric 1:2 resonance, based on the results of (1), we show the resonant behavior and resonant centre for both the symmetric libration and asymmetric libration, which are strongly dependent on the inclination of the 1:2 resonant population; (3) for the 3rd-order 4:7 resonance, we introduce a limiting curve to constrain the eccentricity and inclination distribution of possible 4:7 resonators, as more inclined objects tending to occupy more eccentric orbits; (4) as a generation of the results of (3), our theory is applied to a variety of high-order resonances embedded in the main classical Kuiper belt from 42 to 47 AU, including the 3:5, 4:7, 5:9, 6:11, 7:12, 7:13 resonances, and we make predictions for the number and orbital distributions of potential resonant objects for all these high-order resonances. In addition to the above theoretical results, by numerical simulations, we further provide new ways to reconcile the origin and evolution of resonant high-inclination KBOs with our current understanding of the formation of the outer solar system.
Authors: Jian Li, Li-Yong Zhou, S. M. Lawler, Hanlun Lei, Yi-Sui Sun.

Forming Super-Mercuries: Role of stellar abundances, by Jingyi Mah[1]
[1] Max Planck Institute for Astronomy
In a recent work (Mastroianni and Efthymiopoulos 2023) we revisit the problem of understanding the structure of the phase space of the secular 3D planetary three body problem, focusing on the transition, as the level of mutual inclination increases, from a 'planar-like' to the 'Lidov-Kozai' regime. Using a typical 'non-hierarchical' example, we find that the phase-space structure of the integrable dynamics of the planar case is reproduced to a large extent also in the 3D case. In particular, we provide a semi-analytical criterion allowing to estimate the extent in mutual inclination up to which dynamics remains nearly-integrable ('planar-like'). In this regime, a suitable normal form allows to recover semi-analytical expressions for the basic periodic orbits (apsidal corotation orbits). On the other hand, we show how, as the mutual inclination increases, the system gradually moves from the 'planar-like' to the 'Lidov-Kozai' regime. The latter is dominated by two different families of nearly circular and highly inclined periodic orbits, of which one becomes unstable via the usual Lidov-Kozai mechanism. We show how the latter families are connected to the apsidal corotation families via a chain of saddle-node bifurcations. Through a numerical study for different mass and semi-major axis ratios of the two planets, we discuss how generic are the above phenomena, as well as the approach to one or more hierarchical limits.

The phase-space architecture in the secular 3D planetary three-body problem, by Rita Mastroianni[1]
[1] University of Padua
In a recent work (Mastroianni and Efthymiopoulos 2023) we revisit the problem of understanding the structure of the phase space of the secular 3D planetary three body problem, focusing on the transition, as the level of mutual inclination increases, from a 'planar-like' to the 'Lidov-Kozai' regime. Using a typical 'non-hierarchical' example, we find that the phase-space structure of the integrable dynamics of the planar case is reproduced to a large extent also in the 3D case. In particular, we provide a semi-analytical criterion allowing to estimate the extent in mutual inclination up to which dynamics remains nearly-integrable ('planar-like'). In this regime, a suitable normal form allows to recover semi-analytical expressions for the basic periodic orbits (apsidal corotation orbits). On the other hand, we show how, as the mutual inclination increases, the system gradually moves from the 'planar-like' to the 'Lidov-Kozai' regime. The latter is dominated by two different families of nearly circular and highly inclined periodic orbits, of which one becomes unstable via the usual Lidov-Kozai mechanism. We show how the latter families are connected to the apsidal corotation families via a chain of saddle-node bifurcations. Through a numerical study for different mass and semi-major axis ratios of the two planets, we discuss how generic are the above phenomena, as well as the approach to one or more hierarchical limits.

Timescales of chaos in the inner Solar System: Lyapunov spectrum and quasi-integrals

of motion, by Federico Mogavero[1]
[1] Institut de mécanique céleste et de calcul des éphémérides (IMCCE)
Numerical integrations of the Solar System reveal a remarkable stability of the orbits of the inner planets over billions of years, in spite of their chaotic variations characterized by a Lyapunov time of only 5 million years and the lack of integrals of motion able to constrain their dynamics. To open a window on such long-term behavior, we compute the entire Lyapunov spectrum of a forced secular model of the inner planets. We uncover a hierarchy of characteristic exponents that spans two orders of magnitude, manifesting a slow-fast dynamics with a broad separation of timescales. A systematic analysis of the Fourier harmonics of the Hamiltonian, based on computer algebra, reveals three symmetries that characterize the strongest resonances responsible for the orbital chaos. These symmetries are only broken by weak resonances, leading to the existence of quasi-integrals of motion that are shown to relate to the smallest Lyapunov exponents. A principal component analysis of the orbital solutions independently confirms that the quasi-integrals are among the slowest degrees of freedom of the dynamics. Strong evidence emerges that they effectively constrain the chaotic diffusion of the orbits, playing a crucial role in the statistical stability over the Solar System lifetime.

Challenges of the catalogue building and maintenance based on optical survey of tge LEO region, by Alexis Petit[1]
[1] Share My Space
Exoplanet transit surveys have revealed the existence of numerous multi-planetary systems packed close to their stability limit. The majority of these exoplanet systems lie in-between the main two-planet resonances. I will show how the dynamics governing the stability of such systems is dominated by the interactions between the resonances involving triplets of planets. The complex network of three-planet mean motion resonances drives a slow diffusion of the semi-major axes, that can lead to the destabilization of the system on short timescales. This process reproduces quantitatively the timescale of instability obtained numerically over several order of magnitude in time and planet-to-star mass ratios. As this dynamical process dominates the dynamical rearrangement of planetary systems at the end of their formation, we observe on the system's architecture signpost of these events.

Forming the Trappist-1 system in two steps during the recession of the disc inner edge, by Gabriele Pichierri[1]
[1] Caltech
Exoplanet transit surveys have revealed the existence of numerous multi-planetary systems packed close to their stability limit. The majority of these exoplanet systems lie in-between the main two-planet resonances. I will show how the dynamics governing the stability of such systems is dominated by the interactions between the resonances involving triplets of planets. The complex network of three-planet mean motion resonances drives a slow diffusion of the semi-major axes, that can lead to the destabilization of the system on short timescales. This process reproduces quantitatively the timescale of instability obtained numerically over several order of magnitude in time and planet-to-star mass ratios. As this dynamical process dominates the dynamical rearrangement of planetary systems at the end of their formation, we observe on the system's architecture signpost of these events.

Inward and outward scattering of Oort cloud comets due to Gliese 710, by Elke Pilat-Lohinger[1]
[1] University of Vienna
Observations and orbit computations of the K-star Gliese 710 indicate a stellar encounter with the solar system in about 1.3 Myrs where recent GAIA DR 3 data suggests a fly-by at a distance of 10500 au from the Sun. Thus, Gliese 710 will cross the spherical Oort cloud and scatter comets either into the interstellar space or towards the Sun. Using our GPU N-body integrator we are able to compute more than 200 million Oort cloud comets that are randomly distributed in a cylinder around path of Gliese 710 whose size is defined by the sphere of influence. Considering such a high number of

comets, the density is comparable with the real density of the Oort cloud. During the stellar passage, about half of the comets in the cylinder will be scattered into the interstellar space. In addition, several thousands of Oort cloud comets will enter the observable region of the solar system which might increase the impact probability on Earth after this stellar fly-by.
Authors: E.Pilat-Lohinger, B. Loibnegger, M. Zimmermann and D. Hestroffer

Normal forms for Laplace-like resonances, by Giuseppe Pucacco[1]
[1] University of Rome Tor Vergata
We describe the generalization of the de Sitter equilibria in multi-resonant 1+3 body systems in the case of first-order resonances. It is shown that, under certain conditions on the proximity parameter to the exact resonance, additional equilibria with large forced eccentricities are possible. The analysis of stability provides hints for the structure of multi-resonant chains in exo-planetary systems.

Non-Keplerian Motion of Trans-Neptunian Binaries: Shapes, Spins, and Formation, by Darin Ragozzine[1]
[1] Brigham Young University
Trans-Neptunian Object Binaries (TNBs) provide unique insights into the formation of the solar system. Previous analyses of TNB orbits almost exclusively assume Keplerian orbits. Using a new n-quadrupole integrator coupled with a new analysis of astrometric data using Bayesian parameter inference, we re-analyze all TNBs allowing for basic non-Keplerian orbits. We find several TNBs with strong evidence for non-Keplerian motion. This includes large objects like Eris (where we find evidence for an unseen interior moon) and small "cold classical" TNBs. Many cold classical TNBs are consistent with highly elongated shapes and/or unresolved hierarchical triples. This supports the theory that cold classical TNBs formed in situ through the gravitational collapse of solids concentrated by the streaming instability. We will discuss how non-Keplerian orbit fitting is opening our understanding of the shapes, spins, and formation of TNBs.

Resonantly amplified tidal dissipation in the fluid layers of planets and moons, by Jérémy Rekier[1]
[1] Royal Observatory of Belgium
Tidal deformation of planets and moons contributes to dissipating orbital and rotational energy in the form of heat. This process is believed to be the source of the strong geothermal activity observed in the icy moons of Jupiter and Saturn, yet it remains at present not fully understood. Tidal dissipation in gas giants is also believed to play an important role in their evolution and on the orbital dynamics of their moons. In both cases, the dissipation maybe resonantly amplified by free modes of oscillations in fluid layers (liquid core, global subsurface ocean, atmosphere of gas giants) whose frequencies depend on internal structure. We present a method to compute the free oscillations of rotating planetary fluid layers and the associated dissipation, focusing specifically on the set of inertial modes whose frequencies closely match typical tidal excitation frequencies. We explore the dependence of these modes on the internal properties of their host planetary body, including density stratification and a magnetic field.

Dynamical evolution and heat dissipation in the Trappist-1 system, by Alexandre Revol[1]
[1] Geneva Observatory
Half of the 5000 exoplanets discovered up to now have an orbital period less than 10 days, and therefore experience some form of tidal evolution. Tides lead to exchange of angular momentum between the planets and their host star, and drive planetary spin evolutions and influence orbital evolutions. Tides can also influence the internal state by the dissipation of a large mouth of energy by internal friction, driving the thermal state of planets or satellites, as is the case of Io, the most volcanic active body of the Solar System (Renaud et al. 2018, Kervazo et al. 2021). This heat dissipation must be considered with care in habitability studies of close-in rocky planets, as in extreme cases, it can trigger

a runaway greenhouse state (Barnes et al. 2013). In less extreme case, it could trigger plate tectonic (Zanazzi & Triaud 2019) and change the chemical composition of the atmosphere by the release of volcanic gases.In the context of the arrival of the new generation of instruments, as the JWST (Greene et al. 2016), for the characterization of close-in rocky planets, the correct modeling of the dynamical state of exoplanets is crucial to constrain their surface condition. We need to consider a relevant model of tides for rocky exoplanets to better characterize their surface conditions and heat budget. Tidal models using a simple prescription, as the Constant Time Lag (e.g. Hut 1981, Goldreich & Soter 1966), are relevant for weakly viscous objects, but they should not be used for high viscous objects as rocky planets (Henning et al. 2009, Efroimsky & Makarov 2013). In contrast, we use here a model more relevant for high viscous object, which accounts for more realistic anelastic behavior for the rocks (such as the Andrade rheology). We use a development proposed by Kaula (1964), consisting on the decomposition of the tidal potential into Fourier harmonic modes. The recent implementation of this framework in the N-body code Posidonius (Blanco-Cuaresma & Bolmont 2017, Bolmont et al. 2020b) allows us to study the dynamical evolution and the heating budget of multi-planet systems such as the Trappist-1 system (Gillon et al. 2017). We use the latest estimates of the mass and radius of the planets, and construct internal profiles with the BurnMan code (Cottaar 2014, Myhill 2022). This then allows us to compute the frequency dependence of the Love number following the method described in Tobie et al. (2005). We explore the different possible evolutions of the system with the uncertainties that remain on the internal structure in terms of core size and composition. We will present our firsts results on the long terms dynamical evolution of the Trappsit-1 system using the Kaula formalism. In particular, we will show the orbital and rotational evolution of the system in an N-body code, with a realistic model of tides and internal structures to provide insight on the dynamical and thermal heating within the Trappist-1 system.

Mapping the structure of the planetary 2:1 mean motion resonance: the TOI-216, K2-24, and HD27894 systems, by Adrian Rodriguez[1]

[1] Valongo Observatory, Federal University of Rio de Janeiro

Mean motion resonances (MMR) are a frequent phenomenon among extrasolar planetary systems. Current observations indicate that many systems have planets that are close to or inside the 2:1 MMR, when the orbital period of one of the planets is twice the other. Analytical models to describe this particular MMR can only be reduced to integrable approximations in a few specific cases. While there are successful approaches to the study of this MMR in the case of very elliptic and/or very inclined orbits using semi-analytical or semi-numerical methods, these may not be enough to completely understand the resonant dynamics. In this work, we propose to apply a well-established numerical method to assess the global portrait of the resonant dynamics, which consists in constructing dynamical maps. Combining these maps with the results from a semi-analytical method, helps to better understand the underlying dynamics of the 2:1 MMR, and to identify the behaviors that can be expected in different regions of the phase space and for different values of the model parameters. We verify that the family of stable resonant equilibria bifurcate from symmetric to asymmetric librations, depending on the mass ratio and eccentricities of the resonant planets pair. This introduces new structures in the phase space, that turns the classical V-shape of the MMR, in the semi-major axis versus eccentricity space, into a sand clock shape. We construct dynamical maps for three extrasolar planetary systems, TOI-216, HD27894, and K2-24, and discuss their phase space structure and their stability in the light of the orbital fits available in the literature.

Network perspective to study the state of Earth's orbital traffic, by Matteo Romano[1]

[1] University of Namur

With only a fraction of the 32000 catalogued objects orbiting Earth being active satellites, space around our planet is steadily becoming littered with unusable artificial bodies and debris produced in regular fragmentation events. The current space traffic management practices focus on single encounters between objects to evaluate the probability of collisions, however losing sight on the larger picture

of the space resident population and the continuous conjunctions increasing the risk of collisions and their effects. Following the approach proposed within the WALSAT project, the population is represented via a network, which maps the conjunctions between the catalogued space residents, from a complex system perspective. The information about the probability of collisions and the properties of the network are combined, obtaining a global estimation of the risk and consequences of fragmentations and changes in the population. This method is used to formulate criteria to judge the hazard level of the population and guide the creation of new standards for space situational awareness.
This is a joint work with Timoteo Carletti and Jérôme Daquin

Dynamical asymmetries for L4/L5 captures, by Mattia Rossi[1]
[1] University of Padova
Captures of small bodies in the neighborhood of the L4/L5 points of a planet are driven by the heteroclinic dynamics connecting the invariant manifolds emanating from periodic orbits around the L3 and L2 unstable equilibria. The talk will discuss the asymmetries observed in numerical experiments as regards the inflow of particles towards the L4 and L5 region of a migrating planet. An analysis of such asymmetries will be presented based on the asymmetries in the distribution of heteroclinic connections between the manifolds (stable and unstable) involved in the capture process.

Oblique rings as a natural end state of migrating exomoons, by Melaine Saillenfest[1]
[1] IMCCE, Observatoire de Paris
Moons alter the spin-axis precession rate of their host planet. The tidal migration of moons is therefore an efficient driver of resonance crossing between the spin-axis and orbital precession modes of a planet. We examine the relevance of this mechanism for the exoplanet HIP41378f, and show that a former satellite with roughly the mass of our Moon would be able to tilt the planet to nearly 90°. At this point, the moon becomes unstable and may be disrupted into a ring of debris. In transit data, such an oblique ring can be misinterpreted as an inflated radius. This phenomenon is a viable alternative to the – otherwise unexplained – very low density of HIP41378f.

Resonances around small bodies of the solar system: where should be the rings?, by Bruno Sicardy[1,2]
[1] Sorbonne University
[2] Paris Observatory
As to January 2023, three ring systems have been discovered around small bodies of the outer solar system: one around the Centaur Object Chariklo and two around the dwarf planets Haumea and Quoar, respectively. In spite of large differences in mass, sizes and heliocentric distances, all these rings lie close to the 1/3 Spin-Orbit Resonance (SOR) with the central body, meaning that a ring particle completes one revolution while the central body completes three rotations. The question is to know whether these configurations are coincidental, or on the contrary associated with a deep mechanism that favors the presence of rings at or near this resonance. Contrarily to the giant planets, which are essentially axisymmetric, small bodies are irregular and may possess significant mass anomalies, triaxial shapes or more complex structures. Here I will present calculations to estimate the strengths of various SORs around irregular small bodies. The first-order SORs around Chariklo, Haumea and Quoar appear to be very strong, considering their estimated triaxial shapes. In particular, the outermost 2/3 resonance is likely to rapid push away any initial collisional disk surrounding the body. The same is true with the outermost 2/4 second-order SOR. Moving outwards, the next strongest resonance is the second-order 1/3 SOR excited by a mass anomaly inside the body. I will discuss the topology of its phase portrait, in particular the fact that ring particles will have their orbital eccentricities forced in a narrow interval of semi-major axes surrounding this resonance. Numerical simulations of collisional ring systems near the 1/3 SOR with Chariklo confirm that this resonance may in fact excit', but also show that they may confine the ring. A special case in Quoar's ring. The 1/3 SOR lies at a large distance from the body, more than 7.4 Quaoar's radii. This is well outside the

classical Roche limit, about 3 Quaoar's radii. At that distance, a ring should accrete into a satellite on a very short time scale (a few years), and thus disappear. I will discuss here the possibility to maintain such a ring by considering collisions that are more elastic than previously estimated. The work leading to these results has received funding from the European Research Council under the European Community's H2020 2014-2021 ERC Grant Agreement no. 669416 ”LuckyStar”.

Dynamics of a triple system comprising an inner binary black hole in a mutually inclined orbit, by Yasushi Suto[1]

[1] The University of Tokyo

The LIGO-VIRGO collaboration has discovered a plenty of massive binary black-holes (BBHs) via their gravitational wave emission. This suggests even more abundant binary black-hole systems that are in a wider separation and thus remain undetected in the gravitational wave. Several ongoing surveys, notably by TESS and Gaia missions, are likely to discover star-black hole binaries in our Galaxy in the near future. A fraction of them may be triple systems comprising an inner binary, instead of a single black hole. They may be progenitors of the BBHs discovered routinely from the gravitational wave. If such a star-binary black-hole system exists in our Galaxy, its outer tertiary star should exhibit a radial velocity modulation reflecting the nature of the inner binary. Combining an analytic approximation based the quadruple perturbation theory and N-body simulations of such triples, we examined the detectability of wide-separation inner BBHs in the Galaxy from the characteristic signals of the radial velocity of the tertiary star. The resulting radial velocities consist of two different types of modulations. First is a short-term radial-velocity variation of roughly twice the orbital frequency of the inner BBH. The amplitude is about 1 percent of its Kepler orbital velocity. The other is a long-term modulation in significantly inclined triples in which the semi-amplitude of the entire radial velocity is modulated periodically by the precession of the inner and outer orbits over roughly the von Zeipel-Kozai-Lidov oscillation timescale. The amplitude of the secular modulation depends on the observer's line of sight, but can be on the order of 100 km/s. The modulation timescale is usually long, but if the outer orbital period is relatively short to the order of months, it is quite feasible to detect the modulation over 10-year scales for instance. Therefore, we conclude that the radial velocity monitoring of future star-black hole binary candidates offers a promising method for searching for triple systems including black hole and possibly their inner hidden BBHs, in optical bands.

Encounter manifolds in the Solar System. Preliminary results, by Nataša Todorović[1]

[1] Astronomical Observatory of Belgrade

It is generally accepted that chaos is present almost everywhere in the Solar System. Recent numerical studies have shown that such chaos is not completely disordered. Namely, the entire solar system is permeated with certain parts, which appear as arch-like structures (in the semi-major axis - eccentricity plane) that show instability in extremely short times. More precisely, particles placed on such arches experience planetary encounters (ending up in collisions, escapes, planetary trappings or transitions) after only one or few orbital revolutions. First observed in 2020, these arches still don't have a proper analytical explanation, and their general structure in phase space remains unknown. Here we will show some preliminary results of our numerical research, aimed at better understanding and displaying these encounter manifolds in three dimensions.

On the predictability horizon in Impact Monitoring of NEOs, by Giacomo Tommei[1]

[1] University of Pisa

Current NEO Impact Monitoring (IM) systems (Aegis, NEODyS and Sentry) scan the Confidence Region (CR) of each available object looking for Virtual Impactors (VIs) 100 years into the future. This procedure is performed regardless of the uncertainty with which the orbit of the object is known, and without considering if a scattering encounter is present in the propagation time span. Thinking of the future increase in cases to be treated, it might be more reasonable to adapt the predictability horizon of the impacts to the single object, taking into account the orbit uncertainty and the close encounters experienced. In this talk I will introduce the problem and try to provide some possible solutions.

Gap Structure Created by Satellite Embedded in Saturn's Ring, by Naoya Torii[1]
[1] Tokyo Institute of Technology
Cassini observation revealed various kinds of beautiful and interesting structures in Saturn's ring. These structures is thought to be created by the physical interaction between ring particles and satellite. We are focusing on the gap structure created by the interaction between satellite embedded in the ring (e.g. Daphnis and Pan) and ring particles. It is known that the edge of these gap is sharply cut and density wave appears on the edge of the gap. Its physical mechanism was suggested in previous studies and it has been demonstrated by local N-body simulation so far (e.g. Borders et al. 1982, Lewis & Stewart 2000). However, it is not clear whether we can completely understand the physics in Saturn's ring only with local simulation. In order to understand these physical structures comprehensively, we carried out the global N-body simulation of gap structure created by satellite taking into account of self-gravity and inelastic collision between particles. We used GPLUM code which was developed for planetary formation. The number of particles was about 10^5 and we carried out several runs changing satellite mass. As a result, we were able to reproduce sharp edge, density wave and wall-like vertical structure. All these characteristic features were revealed by Cassini observation in fact. In this talk, I will introduce these series of simulation results and discuss about its dependence on satellite mass.

Excitation of the obliquity of Earth-like planets via tidal forcing, by Ema Valente[1]
[1] CFisUC Department of Physics,Coimbra University
Close-in planets undergo strong tidal interactions with the parent star that modify their spins and orbits. It is commonly assumed that the rotation of this planets is synchronous and the planet spin axis is aligned with the normal to the orbit (zero planet obliquity). Here we show that, for non-zero eccentricities, the rotation rate can be trapped in spin–orbit resonances that delay the evolution towards the synchronous state. More interestingly, we observe that capture in some spin-orbit resonances may also excite the obliquity to high values rather than damp it to zero. Depending on the system parameters, obliquities up to 80 degrees can be maintained throughout the entire lifetime of the planet. This unexpected behaviour is particularly important for Earth-like planets in the habitable zone of M-dwarf stars, as it may help to sustain temperate environments and thus more favourable conditions for life.

Partial Banana Mapping: search for close encounters and impact probability, by Dmitrii Vavilov[1]
[1] IMCCE, Paris observatory
For a large set of asteroids – in particular newly discovered NEAs – the precise orbits are unknown. The area of possible positions of an asteroid (uncertainty region) can be large, and even reach the whole revolution around the Sun, while being extremely thin and stretched mostly along the nominal orbit of an asteroid. Because of that, the close approach data of asteroids is generally incomplete. On the other hand, a nominal position of an asteroid can be far from the Earth, but at the same time the asteroid can actually have a close approach or even collide with the Earth. This is one of the reasons why different centers for asteroid dynamics study (Minor Planet Center, Jet Propulsion Laboratory NASA, IMCCE, . . .) publish different results for asteroids close approach data [1]: They have different nominal solutions that lead to difference in outcome. In this work, we are using the 'Partial Banana Mapping' method to compute possible close approach information (time and minimal distance) of an asteroid with the Earth, including the probability of a close approach. We assume that the errors of equinoctial orbital elements have Gaussian distribution during the whole period of consideration (this Century). This assumption is quite reasonable and allows us to take into account the fact that

uncertainty region looks like a thin curvilinear ellipsoid stretched mostly along the nominal asteroid's orbit. We propagate the orbit of the asteroid until the Earth comes close to the uncertainty region. Then we find the point on the main line of curvilinear uncertainty ellipsoid which is closest to the Earth. We construct the uncertainty region around this point in 3D space and map it onto the target plane. With that, we can eventually compute with more accuracy the minimal possible distance of the close approach, the time when it can happen, and the probability of such an event.
Authors: D. E. Vavilov, D. Hestroffer and J. Desmars
Reference: 1. A. Ivantsov et al. (2019) conference 'Dynamics and physics of asteroids, TNOS and natural satellites in the new era of GAIA data'

Analytical representation for the numerical ephemeris of Titan within short time spans, by Xiao Jin Xi[1]
[1] National Time Service Center, Chinese academy of sciences
Numerical integration ephemerides are widely used in research and engineering for their high precision. However, subject to their finite available time spans, their use is limited in theoretical research, such as the studies of rotation and evolution. Previously, we successfully experimented on the analytical representation of the mean longitude of Titan of the Jet Propulsion Laboratory (JPL) ephemeris, as a function of combinations of proper frequencies, and related the results with what is given in the synthetic ephemerides obtained by the Théorie Analytique des Satellites de Saturne (TASS). In this study, the analytical representations of the other osculating elements of the JPL Titan ephemeris are accomplished in order to construct the new synthetic representations, which have the advantages of both systems: long-lasting stability, the system details of TASS, and the high precision of JPL. A frequency analysis process was used to obtain the proper frequencies, amplitudes, and phases of the two ephemerides in the short-term and the semi-long terms. For the proper frequency of the ascending node of Titan, which has a very long period, it is challenging to acquire the exact value, and the formula of TASS was used. The amplitude and phase of long terms were further calculated by a least-squares procedure. Thanks to the accomplishments of the new synthetic representations of the JPL ephemeris, we report the complete combinations of the osculating elements of Titan. These combinations contain important dynamical information such as the proper frequencies. They will be useful in theoretical research.

Mars rotational elements and their quadratic behavior, by Marie Yseboodt[1]
[1] Royal Observatory of Belgium
In order to describe the orientation of the spin axis of Mars, the radioscience community commonly uses Euler angles, with obliquity and node longitude defined with respect to the planet mean orbit at epoch. The IAU Working Group on Cartographic Coordinates and Rotational Elements (WGCCRE) uses the right ascension and declination angles, the equatorial coordinates orienting the planet with respect to the Earth equator in J2000. In both sets of coordinates, a third angle, which has a diurnal periodicity, is used to position the prime meridian. The usual way to transform Euler angles into IAU angles is to numerically evaluate the IAU angles over a given time interval with the help of spherical geometry, then to perform a frequency analysis on the so-obtained time series (e.g. Jacobson 2010, Kuchynka et al. 2014 and Jacobson et al. 2018 for Mars). Unfortunately, such a method does not take into account the physical meaning of the planet's rotational dynamics, which relies on well-known periodicities governed by the celestial mechanics. We explain the analytical expressions to precisely transform one set of angles into the other in the case of Mars. Each angle is modeled by the sum of a quadratic polynomial, a periodic series (nutation or rotation variations) and a Poisson series (a periodic series with amplitudes changing linearly with time). The targeted precision of the transformation is 0.1 mas for each angle on an interval of about 30 years before and after J2000. Even when no quadratic terms exist in a Mars rotation model expressed with Euler angles, the corresponding model with IAU angles does have quadratic terms coming from the transformation. Current IAU-like solutions present very long period signals that result from the absence of a quadratic term in the

model used. Such a long period signal has an amplitude, a phase and a frequency specifically chosen to mimic the quadratic behavior over an interval of a few decades around J2000. Adding a long period modulation instead of a quadratic term largely and artificially alters the angle values at J2000 as well as their rates. We compare the solutions of different authors, including the change in the rotation angle value.

Tidal orbital evolution of circumbinary planets, by Federico Zoppetti[1]
[1] Observatorio Astronómico de Córdoba - Universidad Nacional de Córdoba
Most confirmed circumbinary planets are located very close to their host binary where the tidal forces are expected to play an important role in their dynamics. Here we consider the orbital evolution of a circumbinary planet with arbitrary viscosity, subjected to tides due to both central stars. We adopt the creep tide theory and assume that the planet is the only extended body in the system and that its orbital evolution occurs after acquiring its pseudo-synchronous stationary rotational state. With this aim, we first performed a set of numerical integrations of the tidal equations, using a Kepler-38-type system as a working example. For this case we find that the amount of planetary tidal migration and also, curiously, its direction both depend on the viscosity. However, the effect of tides on its eccentricity and pericenter evolutions is simply a move toward pure gravitational secular solutions. Then we present a secular analytical model for the planetary semimajor axis and eccentricity evolution that reproduces very well the mean behavior of the full tidal equations and provides a simple criterion to determine the migration directions of the circumbinary planets. This criterion predicts that some of the confirmed circumbinary planets are tidally migrating inward, but others are migrating outward. However, the typical timescales are predicted to be very long, and not much orbital tidal evolution is expected to have taken place in these systems. Finally, we revisit the orbital evolution of a circumbinary planet in the framework of the constant time lag model. We find that the results predicted with this formalism are identical to those obtained with creep theory in the limit of gaseous bodies.

POSTERS

P1 - Machine Learning Applied to Filter Meteoroid Impacts in the Atmosphere, by Simon Anghel[1]

[1] Astronomical Institute of the Romanian Academy

The rise in data collection and storage capabilities introduced a challenge for both finding connections between data sets and extracting the valuable information. This phenomenon is also found in meteor science, when false meteor detections make their way in trajectory computations, and will lead to erroneous orbits. During this talk, a set of machine learning (ML) methods will be presented, along with their capability to classify the meteors detected in Meteorites Orbits Reconstruction by Optical Imaging network (MOROI) between 2017-2020. First, a set of regression based features were extracted from the meteor centroid in each frame, next the ML models were tested and tuned to obtain the highest score. The Neural networks method was found to best filter out the false meteors, with a recall score of 96%, followed by 95% for Gradient Boost and Random Forest algorithms. When combining this with the spatio-temporal data from other stations, the recall increases to 99.92%. The results entail follow-up studies on the larger FRIPON network, which is already collecting data in realtime.

P2 - The genesis of exotrojans in PDS 70, by Olga Balsalobre Ruza[1]

[1] Centro de Astrobiología (CAB), INTA-CSIC

The planets in the Solar System are known to be accompanied by co-orbital asteroids populating the Lagrangian points L4 and L5, the so-called trojans. Theoretically, these locations could host bodies as massive as the main planet. The search for siblings of exoplanets in these peculiar zeroth order of resonance has already begun. Hydrodynamical simulations show that dust trapping in Lagrangian points is a natural product of planet formation, which could eventually be the seeds of trojans. In this talk, we present a pilot study to investigate the presence of trojans in PDS 70, the only system with two confirmed protoplanets. Our main result is a tentative detection of dust accumulation in one of the Lagrangian points of the planet PDS 70b. Future observations will allow to confirm the nature of our detection.

P3 - Protoplanet Collisions: Second Generation Scaling Laws, by Samuele Crespi[1]

[1] New York University Abu Dhabi

The last stage of terrestrial planets formation is largely driven by collisions between planetesimals and planetary embryos. These collisions span a broad range of configurations, ranging from the perfect merging of the two colliding bodies to catastrophic collisions, in which no major body survives and the entire colliding mass is fragmented.Simulations of this formation stage face the problem of solving hundreds to thousands of collisions per simulation. The most simple approach is to assume all the collisions result in the inelastic merging between colliders. However, different studies have shown that this assumption can significantly affect the dynamic and chemical properties of the formed planets.A more sophisticated approach is to solve collisions by employing analytical scaling laws and to include in the simulations the two large post-collisional bodies only. The most used scaling laws have been formulated by Leinhardt & Stewart 2012 from a collection of around 180 simulations of collisions between planetesimals. In the past couple of years, however, more than 20,000 new simulations of collisions have been performed and possible improvements of the current scaling laws are now feasible.A decade after the seminal work of Leinhardt & Stewart 2012, we present a new set of scaling laws that are able to more accurately reproduce the outcome of collisions between planetary embryos. Our new model consists in a continuous and differentiable 4-dimensional parametric curve that is capable of reaching prediction levels comparable to machine learning analysis, in particular for high-energetic collisions, and of accurately predicting the collision outcome in all the different regimes, from merging to catastrophic disruption.

P4 - Towards a complete picture of the evolution of planetary systems around evolved stars, by Mats Esseldeurs[1]

[1] KU Leuven
About 95% of all stars in the galaxy have an initial mass lower than 8 solar masses. When these stars evolve off the Main Sequence, they will go through the Asymptotic Giant Branch (AGB) phase, just before turning into a White Dwarf (WD). This evolutionary phase is characterized by significant mass loss, large stellar radii, strong pulsations, and extreme luminosities. It must be studied to get a complete picture of the evolution of planetary systems from the birth to the end of their host stars. Indeed, population synthesis studies indicate that the majority of these stars have at least one (sub)stellar companion, where the abrupt changes in stellar characteristics may completely transform a planetary/binary system. In order to establish whether the planetary/(sub)stellar companion survives this evolutionary phase, and explain the presence of planets orbiting around WDs, one must study their orbital evolution for which both the stellar mass loss rate and mass accretion efficiency onto the companion and tidal interactions between the star and its companion play an important role. In current literature this is only addressed taking into account the simplest equilibrium tide, with mass-loss rate prescriptions and mass accretion efficiencies now considered outdated. For this reason, the treatment of these processes needs to be improved. First, we now study the dynamical tide, which can exceed the dissipation of the equilibrium tide by 3 orders of magnitude, which needs to be studied all along the evolution of stars. Second, we compute complex 3D hydrodynamic simulations that take into account all the complex components of the wind launching mechanism, as well as the gravitational perturbation of the companion. This makes it possible to account for the companion in simulating the mass loss rates, model for wind Roche Lobe overflow determining the mass accretion efficiency on the companion, as well as simulate the morphological structure of the AGB surroundings created by the companion. This allows us to build step by step coherent models of planetary systems orbiting evolved AGB stars.

P5 - Merging ground-based astrometry with JUICE and Clipper radio-science to improve the estimation of the Galilean moons' dynamics, by Marie Fayolle[1]
[1] Delft University of Technology
The upcoming JUICE and Europa Clipper missions will target the Galilean moons of Jupiter through a series of flybys at Europa, Ganymede and Callisto, followed by an orbital phase around Ganymede for the JUICE spacecraft. The very accurate radio-science data from both missions is expected to bring the moons' state solutions down to unprecedentedly low uncertainty levels. It will also improve our current determination of tidal dissipation parameters, with critical implications regarding the formation and orbital evolution of the Jovian system.The Galilean satellites form a very complex and strongly coupled dynamical system. Unfortunately, the JUICE and Clipper missions will provide a very unbalanced data set with a strong focus on Europa, Ganymede and Callisto, while none of the two missions' nominal scenarios includes flybys of Io. Due to the Laplace resonance between the three inner Galilean moons, the lack of direct constraints on Io's dynamics complicates the inversion and impedes the stability of the radio-science solution. Our current ephemerides solutions for the Galilean satellites, on the other hand, mostly rely on ground-based observations. However, radio-science and astrometry have the potential to be very synergistic data sets. Ground-based data have indeed already been collected for more than a century and can therefore bring invaluable constraints on the long-term dynamics of the system, while radio-science provides more accurate data, yet limited to the missions' timelines (5 years). Furthermore, including astrometry in the inversion process will help building a more balanced set of observations, with better distribution between the Galilean moons. In particular, direct observations of Io are crucial to circumvent the lack of JUICE and/or Clipper flybys around this moon. In this work, we combined existing ground-based astrometry and radar data with simulated radio-science measurements from the JUICE and Europa Clipper spacecraft. We quantified the possible improvement achievable for the estimation solution, focusing on reconstructing the long-term dynamics of the moons and thus looking primarily at the estimated states and tidal dissipation parameters. The contribution of each different data types was individually analysed, distinguishing between old and recent astrometry, mutual phenomena, radar data and stellar occultations. We also

specifically quantified the improvement provided by ground-based observation of Io only. We show that adding astrometry indeed helps stabilising the estimated state solution and can noticeably reduce the uncertainty in tidal dissipation parameters. As expected, astrometric observations of Io efficiently complement the radio-science data set and account for a significant part of the observed improvement. Classical astrometry in general, despite being less accurate than more recent observations, also helps constraining the solution. Overall, the promising results obtained with simulated radio-science motivates future efforts to merge such diverse data sets and try achieving a combined astrometry - radio-science solution when JUICE and Clipper data become available.
Authors: Marie Fayolle, Andrea Magnanini, Valery Lainey, Dominic Dirkx, Marco Zannoni, Paolo Tortora

P6 - Multi-planet systems explored: the case of the HD34445 system revisited, by Nikolaos Georgakarakos[1]
[1] New York University Abu Dhabi
HD34445 is a system that consists of a star and six planets. In some previous work, we investigated the dynamical stability of the system by means of numerical simulations. Here, we explore the system further by carrying out additional numerical experiments. We study certain aspects of the dynamical evolution of the system by taking into consideration potential effects from General Relativity and the possibility of non-coplanarity of the system. Moreover, we investigate the contribution of the outmost planet to the stability of the planetary system. Some preliminary results are presented and discussed.

P7 - Effects of Planetesimal Scattering: Explaining the Observed Offsets from Period Ratios 3:2 and 2:1, by Tuhin Ghosh[1]
[1] Tata Institute of Fundamental Research
The observed deficit and excess of adjacent planet pairs with period ratios narrow and wide of 3:2 and 2:1, the nominal values for the corresponding mean motion resonances (MMRs), have intrigued many. Previously, using a suite of simulations, Chatterjee & Ford (2015) showed that the excess above the 2:1 MMR can be naturally explained if planet pairs, initially trapped in the 2:1 MMR, dynamically interact with nearby planetesimals in a disk. We build on this work by a) updating the census of discovered planet pairs, b) extending the study to initially non-resonant as well as resonant planet pairs, c) using initial planet and orbital properties directly guided by those observed, and d) extending the initial period ratios to include both 2:1 and 3:2. We find that 1) interactions with planetesimals typically increase the period ratios of both initially resonant and non-resonant planet pairs; 2) starting from an initially flat period ratio distribution for systems across 3:2 and 2:1, these interactions can naturally create the deficits observed narrow of these period ratios; 3) contribution from initially resonant planet pairs is needed to explain the observed levels of excess wide of 3:2; 4) a mixture model where $\sim 25\%$ (1%) planet pairs were initially trapped into 3:2 (2:1) MMRs is favored to explain both the observed deficit and excess of systems across these period ratios. However, up to a few percent of planet pairs are expected to remain in MMR today.

P8 - Stability of Systems with Three Giant Planets, by Farhang Habibi[1]
[1] CNRS
Motivated by the discovery of exoplanetary systems with multiple giant planets, we present the results of a systematic study of the long-term stability of systems with three Jupiter-like bodies. We began by carrying out a large number of orbital integrations for different values of the mass, semimajor axis and orbital eccentricities of the planets and identified the regions of the parameter space for which the three-planet system is stable. We then studied the long-term stability of terrestrial-class planets in regions interior to the three giant planets in all stable systems. Results show that terrestrial planets can maintain long-term stable orbits in systems where giant planets are in low-eccentricity orbits. Results also show that despite its mass and eccentricity, the farthest giant planet plays a weaker role in the stability of the inner planets. We present results of our simulations and discuss their implications for

the orbital assembly and formation of terrestrial planets in systems with more than two giant planets.

P9 - Exoplanet Ocean Chemistry in the Presence of Diverse Carbonates, by Kaustubh Hakim[1]

[1] KU Leuven

The carbonate-silicate cycle is thought to play a key role in maintaining temperate climates on Earth via continental silicate weathering and seafloor carbonate precipitation. Present-day carbonate precipitation on Earth's seafloor is mainly attributed to calcium carbonates. However, observations of refractory element ratios in stellar photospheres and planet formation models suggest a large diversity in exoplanet bulk composition and thereby the near-surface composition. In this work, we compute exoplanet ocean pH and carbonate compensation depth (CCD). We find that ocean pH exhibits a limited range of values as a function of ocean temperature and partial pressure of CO_2, where the limits are given by the absence and presence of carbonates. The CCD increases with ocean temperature and partial pressure of CO_2. If the CCD is above the seafloor, the carbonate-silicate cycle ceases to operate and therefore high ocean temperature and partial pressure of CO_2 favor the carbonate-silicate cycle. With the help of pure carbonate systems of key divalent elements, we show that magnesium, calcium and iron carbonates produce an increasingly wider parameter space of deep CCDs, suggesting that chemical diversity promotes the carbonate-silicate cycle. This work motivates the inclusion of more chemically diverse targets than Earth twins in the search for life in exoplanets.

P10 - TBD, by Shuo Huang[1]

[1] Leiden University

The M-dwarf star TRAPPIST-1 is home to seven Earth-sized planets, the largest number ever found in a single-planet system. Three of these planets may be suitable to harbor liquid water or even life and are one of the prime targets for the recently-launched JWST spacecraft. Unlike the terrestrial planets in our solar system, TRAPPIST-1 planets formed early in their gas-rich protoplanet disk. There, planets migrate inwards until they reach the inner edge of the gaseous disk. The current resonant architecture of these planets is crucial to how planets form and migrate. We find that their observed properties can be well explained by sequential planet formation and migration models.

P11 - When where and how many planets are in resonance, by Shuo Huang[1]

[1] Leiden University

The theory of Type I migration theory has been widely used in many studies. Yet, it has not been systematically tested against the observed exo-planets without placing planets in a newly introduced physical scenario (with new free parameters). Transiting multi-planet systems offer us the opportunity to examine the consistency between observation and theory, especially for those systems harboring planets in Mean Motion Resonance (MMR). The displacement these resonant pairs show from exact commensurability provides us with information on their migration and eccentricity-damping histories. Here, we adopt a probabilistic approach, characterized by two distributions – appropriate for either the resonant or non-resonant planets – to fit the observed planet period ratio distribution. With the Markov chain Monte Carlo (MCMC) method, the probability of each planet pair being in resonance is recovered and their overall property is consistent with the theory of migration and eccentricity damping. The fitting results suggest there ≈15% of exoplanets are in first order ($j + 1$:j) resonance. Most of the resonant pairs park themselves at the migration barrier – possibly the dust sublimation radius. Furthermore, after improving the criterion on two-body resonant trapping, we obtain an upper limit of the disc surface density at the time the planets are locked in resonance. It constrains that planets cannot form too early when the observed resonance states are unstable due to rapid migration.

P12 - PhoDyMM: the PhotoDynamical Multi-planet Model by Daniel Jones[1]

[1] BYU

As the study of exoplanets has developed, new observational constraints have illuminated the formation and evolution of planetary systems. Among these observations, the true distributions of planetary mass, radius, and density are at the forefront. The Kepler Space Telescope has provided an enormous wealth of data on the exoplanet radius distribution as well as a significant fraction of mass measurements through the detection of planet-planet dynamical interactions. These interactions have been typically characterized using Transit Timing Variations (TTVs), but TTVs are often either ignored or analyzed independently from the lightcurve. A more self-consistent approach known as a photodynamical model combines an n-body integrator with synthetic light curves. Photodynamical models allow for a more precise inference of planetary densities and enable the study of small planets (which may not have discernable transit times). To support photodynamical modeling, we have developed the PhotoDynamical Multiplanet Model (PhoDyMM) which combines a photodynamical model with a Differential Evolution Markov Chain Monte Carlo (DEMCMC) algorithm for Bayesian parameter inference of the physical and orbital parameters of an arbitrary number of planets. PhoDyMM has already been used in multiple papers on specific systems and we have been making it more flexible so that it can work easily with arbitrary Kepler systems, enabling the self-consistent analysis of all Kepler systems of multiple exoplanets. A preliminary analysis of over 200 Kepler systems has already been completed and the primary analysis of all the Kepler systems with multiple transiting planets is currently in progress. We will present the results for all the Kepler systems for which the PhoDyMM analysis has concluded.

P13 - Analysis of the arm-like structure in the outer disk of PDS 70: spiral density wave or vortex? by Sandrine Juillard[1]
[1] University of Liège
Observing dynamical interactions between planets and disks is key to understanding their formation and evolution. Two protoplanets have recently been discovered within PDS 70's protoplanetary disk, along with an arm-like structure towards the north-west of the star. Our aim is to constrain the morphology and origin of this arm-like structure, and to assess whether it could trace a spiral density wave caused by the dynamical interaction between the planet PDS 70c and the disk. We analyze polarized and angular differential imaging (PDI and ADI) data taken with VLT/SPHERE, spanning six years of observations. PDI data sets are reduced using the IRDAP polarimetric data reduction pipeline, while ADI data sets are processed using MUSTARD, a novel algorithm based on an inverse problem approach to tackle the geometrical biases spoiling the images previously used for the analysis of this disk. We confirm the presence of the arm-like structure in all PDI and ADI datasets. We do not observe a south-east symmetric locus with respect to the disk minor axis, which seems to reject the previous hypothesis that the arm is the footprint of a double-ring structure. If the structure traces a spiral density wave following the motion of PDS 70c, we would expect 11 degrees of rotation for the spiral in six years. However, we do not measure any significant movement of the structure. If the arm-like structure is a planet-driven spiral arm, the observed lack of rotation would suggest that the assumption of rigid-body rotation may be inappropriate for spirals induced by planets. We suggest that the arm-like structure may rather trace a vortex, appearing as a one-armed spiral in scattered light due to projection effects. The vortex hypothesis accounts for both the lack of observed rotation and the presence of a nearby sub-mm continuum asymmetry detected with ALMA. Additional follow-up observations and dedicated hydrodynamical simulations could confirm this hypothesis.

P14 - On retrograde coorbital motion of asteroids by Thomas Kotoulas[1]
[1] Aristotle University of Thessaloniki
We compute planar and three-dimensional retrograde periodic orbits in the vicinity of the restricted three-body problem (RTBP) with the Sun and Neptune as primaries and we concentrate on the dynamics of higher-order exterior mean motion resonances with Neptune. By using the circular planar model as the basic model, families of retrograde symmetric periodic orbits are computed at the 4/5, 7/9, 5/8 and 8/13 resonances. We determine the bifurcation points from the planar circular to the planar elliptic problem and we find all the corresponding families. In order to obtain a global view

of the families of periodic orbits, the eccentricity of the primaries takes values in the whole interval $0 < e < 90°$, then we can obtain families of 3D symmetric retrograde periodic orbits. The linear stability is examined too. Stable periodic orbits are associated with phase space domains of resonant motion where TNOs can be captured. In order to study the phase space structure of the above resonances, we construct dynamical stability maps for the whole inclination interval $(0 < i < 180°)$ by using the well-known "MEGNO Chaos Indicator". Finally, we discuss about TNOs which are currently located at these resonances.

P15 - Accurate Analytical Calculation of Lunar/Solar/Planetary Perturbations in Motion of Earth Artificial Satellites by Sergey Kudryavtsev[1]

[1] Sternberg Astronomical Institute, Moscow State University

We suggest a new analytical technique for calculation of motion perturbations of Earth artificial satellites caused by the gravity attraction of the Moon, the Sun and major planets. First, we use the modern numerical ephemerides of the major planets and the Moon of DE-series (JPL NASA) in order to calculate the values of all components of the corresponding perturbation function with a small sampling step over a long interval of time (usually, several thousand years). Then, the tabulated values of the perturbation function are processed by the author's modification of the spectral analysis method in order to get accurate harmonic series approximating the function over the entire time interval. The feature of the method is that both amplitudes and arguments of the series terms are obtained as high-degree polynomials of time. The large length of the original time interval allows us to better separate terms of close frequencies. Then we use the so-derived series in our general algorithm that allows one to represent the orbital elements of satellite motion by analytical series over a long-term interval. The algorithm was early applied to the accurate analytical calculation of all geodynamical effects on the Earth satellite motion, like the non-central Earth gravity field, precession and nutation of the geoequator, polar motion and both solid Earth and ocean tides. The description of the developed algorithms and the results obtained for the analytical calculation of motion perturbations of Earth artificial satellites due to the Moon, the Sun and major planets over a long interval of time is presented.

P16 - Star-Planets Tidal Interactions: A Case of Study for the Solar System by Sergey Kudryavtsev[1]

[1] Sternberg Astronomical Institute, Moscow State University

Our solar system and stars with exoplanets are natural laboratories for learning the dynamical interactions in complex star-planets systems. In this study we deal with the hypothetical modulating effect of planetary tides on the solar magnetic activity (the solar cycles) that, in turn, may directly or indirectly affects our Earth climate. Specifically, previous works proposing some physical mechanisms of planetary action on the Sun via the tidal forcing have in common that certain quasi-alignments between Venus, Earth and Jupiter ("V-E-J configurations") would provide a basic periodicity of $\approx$ 11.0 yr able to synchronize the operation of solar dynamo with these configurations. Nevertheless, the evidence behind this particular tidal forcing is still debatable. Methods: In this context, we have developed, for the first time, the Sun's tide-generating potential (STGP) in terms of accurate harmonic series, where the effects of various planetary configurations on the STGP are clearly identified and separated. We used a modification of the spectral analysis method devised by Kudryavtsev (J.Geodesy, 77, 829, 2004; Astron. Astrophys., 471, 1069, 2007) that permits an expansion of any function of planetary coordinates to harmonic series over long time intervals. As a result, we have a catalog of 713 harmonic terms characterizing the STGP with a high degree of precision. In this STGP catalog we looked for tidal forcings related to various V-E-J configurations and specifically for terms with periods of $\approx$ 11.0 yr and $\approx$ 22.0 yr. Results: The detected tidal periods range from $\sim$10,000 yr to 1 week, but we found neither $\approx$ 11.0 yr period nor 22.0 yr one in the STGP catalog. The 11-year spectral band is explicitly dominated by Jupiter's orbital motion. The V-E-J configurations do not produce any discernible terms in the STGP spectrum. The planet that contributes the most to the STGP in a three planets configuration, along with Venus and Earth, is Saturn. Conclusions:

A direct physical relevance of planetary tides on the main 11-year-like solar activity cycle is highly improbable. A similar estimation procedure can be generalized to study possible tidal interactions inside the dynamical systems of exoplanets and their parent stars.
Authors: Sergey M. Kudryavtsev, Rodolfo G. Cionco, Willie W.-H. Soon

P17 - Dust ring and gap formation by gas flow induced by low- mass planets: Implications for the architecture of planetary systems by Ayumu Kuwahara[1]
[1] Tokyo Institute of Technology
Recent high-spatial-resolution observations have revealed dust substructures in protoplanetary disks such as rings and gaps, which do not always correlate with gas (e.g., Andrews et al. 2018). Disk-planet interaction is one of the possible origins of the observed dust substructures in disks. Recent hydrodynamical simulations have revealed that a low-mass planet embedded in a disk induces gas flow with a complex three-dimensional structure (e.g., Ormel et al. 2015). A notable feature of the gas flow structure is the outflow of the gas, which occurs in the radial direction of the disk. Because the outflow of the gas could affect the radial drift of dust, it potentially forms these dust substructures in disks and affects planetary growth via pebble accretion. In this study, we investigate the potential of gas flow induced by low-mass planets to sculpt the rings and gaps in the dust profiles. We first perform three-dimensional hydrodynamical simulations, which resolve the local gas flow past a planet. We then calculate the trajectories of dust influenced by the planet-induced gas flow. Finally, we compute the steady-state dust surface density by incorporating the influences of the planet-induced gas flow into a one-dimensional dust advection-diffusion model. The outflow of the gas toward the outside of the planetary orbit inhibits the radial drift of dust, leading to dust accumulation (the dust ring). The outflow toward the inside of the planetary orbit enhances the inward drift of dust, causing dust depletion around the planetary orbit (the dust gap). Under weak turbulence ($\alpha_{diff1ME}$ (Earth mass) generates the dust ring and gap in the distribution of small dust grains (<1 cm) with the radial extent of ∼1—10 times gas scale height around the planetary orbit without creating a gas gap and pressure bump. We found that the response of the spatial distribution of dust to the planet-induced gas flow varies significantly depending on the location of the planet, resulting in the differences in the growth efficiency of planets. The dust gap formation by the planet-induced gas flow is susceptible to occur in the inner region of the disk (10 au), where the efficient growth of the planets via pebble accretion would be achieved. Our results suggest that: (1) the planet-induced gas flow can be considered as a possible origin of the observed dust substructures in disks, and (2) the planet-induced gas flow could determine the architecture of planetary systems, which may be helpful in explaining the current observed period-mass distribution of exoplanets in which the low-mass planets are more frequent than giant planets at < 1 au.
Authors: Ayumu Kuwahara, Hiroyuki Kurokawa, Takayuki Tanigawa, Satoshi Okuzumi, and Shigeru Ida.

P18 - Can the stellar dynamical tide destabilize the resonant chains of planets formed in the disk? by Leon Ka-Wang Kwok[1]
[1] Geneva Observatory, University of Geneva
Resonance chains of planets are a common outcome of planetary formation and evolution in the protoplanetary disks. However, from observations, resonant chains are rare (a famous example would be the TRAPPIST-1 system). This implies that most of these chains are destabilized after the end of the disk phase (Izidoro et al. 2017). In stellar convective regions, tidal dissipation consists of two components, first one is the equilibrium tide, a large-scale circulation to recover the hydrostatic equilibrium due to the presence of the companion (Zahn, 1966). The second one is the dynamical tide, which is the inertial waves driven by the Coriolis acceleration (Ogilvie & Lin, 2007). Stellar tide, particularly the dynamical tide, could contribute to the destabilization of the resonance chains. Due to the resonant nature of the dynamical tide, the tidal excitation frequency could correspond to a resonant frequency of the star, implying that the inner planet could experience a migration boost, disrupting

the resonant chains' fragile stability.However, some previous studies suggest that one of the famous tidal models, the constant angular lag model, is mathematically contradictory (Efroimsky & Makarov 2013) and that the constant time lag model predicts the pseudo-synchronization for terrestrial objects (Makarov & Efroimsky 2013) which is not observed. Furthermore, these models assume a specific & simple frequency dependence, hence they can not account for the complex multiple frequencies dependence. This is particularly important for eccentric objects, as the multiple frequencies dependence can not be ignored. This suggests that we need a better tidal model for better descriptions. We present the results of our investigation on the influence of the stellar dynamical tide on the stability of the resonant chains using the Kaula model (Kaula, 1961) which accounts for the more complex dependency of the dynamical tide. We use the N-body code Posidonius (Blanco-Cuaresma & Bolmont, 2017) where we have implemented the Kaula model and the dynamical tide. The love number spectra are computed with the code used in Astoul & Barker (2021). We performed simulations of the evolution of the resonant chains and studied their stability with initial conditions for multi-planet systems (multi-super-Earth) from Izidoro et al. (2021). We consider both a population of resonant chains and non-resonant chains which are the outcome of their formation models. We tested these initial conditions without tidal effect first to reproduce the dynamics of the resonant chains. We then applied the tidal forces to see whether the dynamical tide would be able to destabilize the resonant chains. We also applied our model to hypothetical systems of massive planet(s).Our work provides insight into whether the dynamical tide is the corresponding physical mechanism to destabilize the resonant chains, and provides the exoplanet community an N-body code with the dynamical tide & Kaula model for further studies in tidal effects for close-in planets/ binary systems.

P19 - Astrometry Unleashed: The Saturnian System by Valery Lainey[1]
[1] IMCCE
During the thirteen years spent in orbit around Saturn before its final plunge, the Cassini probe provided more than ten thousand astrometric observations of moons. Such a large amount of precise data has allowed us to search for extremely small signals in the orbital motion of the Saturnian satellites. These signals can be linked to key physical mechanisms at play in the system, opening the doors to a new vision of the Saturn system. Using more than a century of ground-based astrometric observations, and benefiting from Cassini imaging data, we have studied the orbital motion of all of Saturn's inner and main moons, including those recently discovered by the Cassini probe. We show how astrometry has allowed us to characterize the strong tidal effects acting among the Saturnian system, while assessing the interior characteristics of several moons and their primary. Updated results are presented.

P20 - Sequential Giant Planet Formation in a Substructured Disk by Tommy Chi Ho Lau[1]
[1] LMU Munich
Models of planetary core growth by either planetesimal or pebble accretion are traditionally disconnected from the models of dust evolution and formation of the first gravitationally bound planetesimals. State-of-the-art models typically start with massive planetary cores already present. We aim to study the formation and growth of planetary cores in a pressure bump, motivated by the annular structures observed in protoplanetary disks, starting with submicron-sized dust grains. We connect the models of dust coagulation and drift, planetesimal formation in the streaming instability, gravitational interactions between planetesimals, pebble accretion, planet migration, gas accretion and gap opening into one uniform framework. We find that massive cores in a pressure bump can remain at wide orbits and grow by gas accretion towards gas giants on a timescale of less than 0.5 Myr. Subsequently, one or more planetary gaps are opened in the disk and dust is trapped at the outer pressure bump. Similar to the initial pressure bump, a new generation of planetesimals is formed at the new pressure bump, which again grow by pebble accretion and then by gas accretion. The model demonstrates that sequential planet formation is possible.

P21 - Investigation of the dynamic evolution of planetary systems with isotropically

varying masses by Mukhtar Minglibayev[1]

[1] al-Farabi Kazakh National University, Almaty

Astronomical observations show that the masses of real celestial bodies are variable. Moreover, one can expect that the masses' variability of the parent star and planets may be are a leading factor of evolution of planetary systems. The purpose of this work is to investigate the effect of variation of mass of a parent star and planets on the evolution of such planetary system. It is assumed that all the bodies are spherically symmetric and attract each other according to Newton's law of gravitation. The masses of all bodies change isotropically with different rates and the laws of the mass variation are known. The problem is investigated in the framework of the classical n planetary problem of n+1 bodies with isotropically varying masses [1]. In the first approximation all planets are assumed to move around the parent star along quasi-elliptic orbits which are determined by the corresponding exact solutions of the two-body problem with variable masses (see [1]). Equations of the perturbed motion of the planets are obtained in the canonical form in analogues of Poincare variables. These canonical variables are effective in the case when the analogues of eccentricities and inclinations of the orbits of planets are sufficiently small and may be considered as small parameters. The tedious and time-consuming work on the expansion of perturbing functions in power series in terms of the osculating variables up to the second degree are performed with the aid of the computer algebra system Wolfram Mathematica [2]. Averaging the equations of the perturbed motion over the mean longitudes, in the non-resonant case, we obtain the evolution equations of the system in general form for any n. The resulting system of evolutionary equations includes 4n linear non-autonomous differential equations, the coefficients of which are various complicated functions of time [2]. For example, for the 7-planetary exoplanet system Trappist-1 [3], they consist of 28 differential equations which are separated into two subsystems of 14 equations. In this work, the evolutionary equations for n=3 are explicitly obtained for the study of the K2-3 exoplanetary system [3]. The dynamics of this system for different laws of mass variation of the parent star and planets are analyzed. Various tracks of osculating elements' evolution are studied by numerical methods.

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Authors: M. Zh. Minglibayev, A. N. Prokopenya, A. B. Kosherbayeva

P22 - A survey of the Geostationary Satellite Belt within the ground-based optical system at NRIAG-Egypt by Ahmed Moursi[1]

[1] National Research Institute of Astronomy and Geophysics (NRIAG)

According to the increasing number of Earth-orbiting debris made by humans, especially near Geosynchronous orbit (GEO), it has become essential to understand long-term GEO object behavior by detecting these objects and catalog updating. Ground-based Electro-optical sensors are a cost-effective way to detect objects at GEO altitude. Therefore, the optical observation of space debris and artificial satellites (Optical Satellites Tracking Station (OSTS)) has been established by the National Research Institute of Astronomy and Geophysics (NRIAG) at Kottamia, Egypt. OSTS has also collaborated with International Scientific Optical Network (ISON) for optical observation. The main tasks of this station are developing an efficient optical survey strategy that utilizes the motion of the GEO environment and the known concentrations of current uncontrolled GEO objects to maximize the coverage of GEO space debris while ensuring good visibility/lighting and good information content, test and assess the merit of the new survey strategy through simulation using metrics which include the number of unique objects detected, required telescope movement, and GEO belt coverage; and test and assess the merit of the different survey strategy.

P23 - On the long-term orbital evolution of a satellite revolving around an oblate body by Gabriela-Ana Nadabaica[1]

[1] Faculty of Mathematics, Al.I.Cuza University of Iasi

In the context of a perturbed two body problem, in which the keplerian motion of the small object (the satellite) is perturbed by the oblateness of the central body (the asteroid) and the attraction of a third body (the Sun), we discuss the long-term evolution of the inclination and the longitude of the ascending node of a satellite orbiting an oblate body. To this end, we provide an analytical study describing the location of the Laplace plane as a function of several parameters, such as the magnitude of the forces involved, the distance from the oblate body, the obliquity of the Sun's orbit. This plane, also called the invariable plane, has its normal vector located between the normal vector of the equatorial plane and the normal vector of the Sun's orbital plane. The analytical study is complemented by numerical tests in which there are propagated several orbits within the context of both Cartesian and Hamiltonian approaches.

P24 - Monte Carlo Simulation for the Synthesis of Complex Organic Molecules in Protoplanetary Disks by Yoko Ochiai[1]

[1] Tokyo Institute of Technology

Recent developments in observational techniques have allowed diverse organic molecules to be observed in the universe. In particular, complex organic molecules (COMs) in the interstellar mediums and outer edge of protoplanetary disk have provided us clues in one of the most primitive organic synthesis processes. One of the mechanisms of producing COMs is considered photochemical reaction activated by ultraviolet light and/or cosmic rays that are ubiquitous in space. Many experiments have succeeded in generating COMs in laboratory. For example, Munoz Caro et al. (2002) irradiated ice analogues containing H2O, CH3OH, NH3, CO and CO2 with ultraviolet light that mimic environments experienced by interstellar grains. As a result, they detected more than 20 kinds of organic molecules, including amino acids. However, there are still significant uncertainties in photochemistry and ice chemistry because of technical problems inherent in analysis and observation, for example. Here, we investigate organic molecule synthesis in protoplanetary disks using new Monte Carlo simulation that applies the classical graph-theoretic matrix model for chemical reaction. This method was originally proposed by Takehara et al. (2022) to study sugar synthesis driven by UV irradiation. We have improved it to allow more practical consideration of radicals that play an important role in photochemistry. Molecules in our simulation form only covalent bonds or radicals, and one step of chemical reaction is restricted to the recombination of two different bonds. These constraints allow us to automatically generate chemical reaction pathways without preparing a reaction network. Consequently, we can access the global picture of the formation of any compounds. The result showed rapid increase of amino acids and sugars after UV irradiation stopped. We found that these amino acids are produced by radical reactions rather than the Strecker-type reaction. More detailed formation mechanism and their dependence on the initial composition of the molecules are discussed.

P25 - Effects of evaporation and re-condensation of ice at snow line on crystallinity in a protoplanetary disk by Tamami Okamoto[1]

[1] Tokyo Institute of Tokyo

Crystalline silicates are observed in outer cold regions of a protoplanetary disk although they would be formed by annealing of amorphous precursors in the inner regions of the disk. Although some studies showed that small crystalline silicate dust could be transported to disk outer region, the crystallinity of dust considering size growth is not well-investigated. Arakawa et al. (2021) showed large crystalline silicates could be carried in an evolving disk due to disk wind. However, they did not consider the diffrence of stickness between ice and silicate. On the other hand, although Okamoto & Ida (2022) showed the crystalline abundance increase due to higher stickiness of ice than silicate and decaying icy pebble flux, they did not consider size growth of silicate dust. We performed a 3D Monte Carlo simulation of advection/diffusion of silicate particles in an expanding disk considering dust growth and evaporation and condensation of water. We assumed stickiness of silicate is less than ice, and when particles collide so fast than critical velocity, they are fragmented. We set "annealing line" by $T = 1000$ K and assume all amorphous precursors are annealed inside the snow line. In this simulation, icy pebbles including amorphous precursors grow up fast and drift inward at first. Then, icy pebbles pile up at snow line. As a result, most of silicate dust do not diffuse over snow line and more amorphous silicates are annealed. After that, due to the inward movement of snow line, some crystalline silicates can diffuse over snow line. Therefore, the crystallinity of silicates around 10 au is raised up to 30% for 1 Myr. Finally, since new crystalline silicates are not formed due to the decrease in the disk temprature, crystallinity also decrease throughout the disk. This result is consistent with the observation. Furthermore, if it would be possible to observe the disk crystallinity with high spatial resolution, we could constrain the dust parameter, such as fragmentation velocity.

P26 - A comprehensive homogeneous investigation of orbital ephemeris and transmission spectrum of WASP-19 b by Anitha Rajkumar[1]
[1] Universidad de Atacama
Exoplanets with ultra-short periods ($P < 1$ day) might experience orbital decay due to the tidal dissipation effect with the host star. My current work allows verification of the orbital ephemeris of the WASP-19 b with the availability of long-term high precision photometric and spectroscopic data including 20 unpublished transits from the Danish telescope. This place limits on the modified tidal quality factor Q'_*. The same data allows for a detailed study of the atmospheric properties of WASP-19 b, via transmission photometry and spectroscopy. WASP-19 A is an active host star with its surface littered with starspots, which if not correctly modeled, systematics are introduced into the transit timing measurements and transit depth, which latter affects the exoplanetary transmission spectrum. Additionally the signal from stellar inhomogeneities can outweigh the signal from planetary spectral characteristics (Rackham, B., V., et al. 2022, arXiv, 220109905, submitted to RAS Techniques and Instruments as invited review.). Therefore, to perform a full and complete orbital ephemeris study of WASP-19b requires the modeling of detected starspots. Incidentally, failing to model both occulted and unocculted starspots can skew measurements in the planetary radius affecting the broadband transmission spectrum. Using the transit-starspot model, PRISM we perform the most complete, detailed, homogeneous analysis of all available data to estimate Q'_* and study the atmospheric properties of WASP-19 b with the help of ground-based and space-based archival data.

P27 - Gamma-ray burst Extinction & Survivability by Matan Sadeh[1]
[1] Bar-Ilan University
This paper discusses the effect of gamma-ray bursts (GRBs) on habitable planets and tests the evolutionary throw-back that could be caused by one, while calculating the frequency of the highly energetic and deadly astronomical event to estimate the potential of a mass extinctions on an Earth-like planet. Since there are papers on both extremes (One saying that mass extinctions are a probable outcome of GRBs by T. Piran and one claiming that mass extinction as a result is not likely by A. Loeb). This paper tests different species with different characteristics and their survivability considering the mentioned astronomical event. This of course refers to all the dangerous rays that Earth (as a sample planet) would be exposed to, including UV rays from the sun as a result of ozone depletion caused by the GRB, as well as the attenuation of the rays in water (most creatures selected are aquatic, considering terrestrial animals are more susceptible to dangerous rays as a result of minimal protection, this paper is focused on non-extremes and relevant evolutionary timestamps relevant to modern man coherent with the frequency of GRBs). This could also serve as an explanation as to why no extraterrestrial life forms were found in the galaxy outside of Earth so far.

P28 - Interception in the hyperbolic three-body problem by Tatiana Salnikova[1]

[1] Lomonosov Moscow State University
The classification of the final motions of the three-body problem by J. Chazy had a symmetry in the past and in the future. Numerical examples that appeared later by a number of authors asserted the possibility of exchange and capture in the asymmetric case. Finally, V.M. Alekseev proved by qualitative methods that there is an open set of initial conditions of positive measure leading to the exchange for systems with both positive and negative total energy: hyperbolic-elliptic motions have different bodies receding to infinity in the past and in the future. The nonzero exchange probability in the general case should be discussed separately in specific real situations. In our study, we consider possible capture of cosmic masses in the framework of the plane hyperbolic three-body problem, as well as the plane parabolic three-body problem in the following setting. Let two massive bodies move along their hyperbolic or parabolic trajectories under the influence of mutual gravitational attraction. A satellite moves around the first body in an elliptical orbit in the past. At the moment of the closest approach of the massive bodies, it enters an elliptical orbit around the second body. This is possible if the speed of the satellite relative to the second body at the moment of approach might be less than parabolic. It happens, if speed of the satellite is opposite to the speed of the first body. We call such exchange scheme as interception. We show that there are quite a lot of possible initial conditions, under which interception occurs both in the restricted and in the unrestricted formulation of the problem. Numerical simulations start from restricted three-body problem with zero-mass of satellite. When passing to unrestricted three-body problem, taking under consideration the gravitational attraction of satellite with the small enough mass, the interception effect is preserved. The parabolic-elliptic case is the limiting case of the hyperbolic- elliptic one. The purpose of this investigation is to discuss the conjecture about the formation problem of satellite systems with non-spherical satellites for the planets of the Solar System within the framework of the proposed model, and the use of such a model to describe the possible areas of accumulation of space debris in near-Earth space. We consider the possibility of capturing space objects into near-planetary space and further movement of these objects, and suggest a mathematical model for the formation of irregular (Phobos-type) satellites of the planets. This model justify the hypothesis for the emergence of such planetary satellites due to the interception (exchange) of cosmic masses. The stability of final motions of this type is also discussed - elliptical motion of satellite relative to the second body is not destroyed by the flying away the first one.

P29 - Interactions between planets and debris disks: the role of disk gravity by Antranik Sefilian[1]

[1] Friedrich Schiller University Jena
Planetary systems in general contain not only planets, but also belts of debris similar to the Solar System's asteroid and Kuiper belts. High-resolution observations of such exo-Kuiper belts, or debris disks, frequently reveal complex morphologies such as gaps or double-ringed structures, spirals, and warps. Most existing dynamical models for explaining such morphologies focus on the role of (invoked) massive perturbers such as planets and stellar companions, ignoring the gravitational effects of the disk itself. This assumption, however, may not always be justified, especially in view of observations that debris disks could contain tens of Earth masses in large planetesimals. Here, I will present results showing that the (self-)gravitational potential of debris disks can be important for producing some of the observed disk structures. Namely, I will demonstrate that the long-term (i.e., secular) interaction between a single planet and an external, self-gravitating debris disk can lead to the formation of a wide gap within the disk. The proposed mechanism is based on the occurrence of secular resonances within the disk, which is found to be quite robust even when the disk is less massive than the planet (contrary to what may be naively expected). I will also show that the same mechanism may lead to the launching of a long, one-armed spiral arm beyond the gap, while at the same time the planet's orbital eccentricity is damped. This circularization of the planetary orbit occurs in the absence of planet-planetesimal scattering. Applications of these results for explaining observations will be discussed at length, focusing on three systems: HD 107146, HD 92945, and HD 206893. I will also discuss the implications of these findings for inferring the dynamical masses of debris disks, as well as the

orbital parameters and evolution of planets in debris disk-hosting systems.

P30 - Stability regions in the largest resonant chain planetary system TOI-178 by Rafael Sfair[1]

[1] Eberhard Karls Universität Tübingen

The number of exoplanets detected is constantly growing, many in multi-planetary systems. A remarkable system is TOI-178 which hosts six planets rapidly evolving with orbital periods from 1.9 to 20.7 days and estimated masses ranging from 1.5 to 7.7 M_{Earth}. Besides the peculiar differences in the density of the planets, the five outer planets are in a chain of 2:4:6:9:12 resonance, one of the largest Laplace resonant chains known to date. This particular orbital configuration raises questions about how this intricate dynamics shapes the stability regions within the system. Thus, we carried out numerical simulations considering 1x106 test particles radially distributed encompassing the entire region of the planets and integrated the system for 500 years. We determined the limits in the (a, e) space where particles may survive and recorded a large number of close encounters, mainly with the most massive planets (TOI-178f and TOI-178g). Temporary captures by all planets were detected, with a more significant probability with TOI-178c. This led us to investigate the evolution of putative trojan objects initially placed in each planet's L4 and L5 regions. Our results show that all planets can keep particles in tadpole orbits, with TOI178-f trojans being the most stable. Furthermore, no significant asymmetry was found between the two Lagrangian points.

Authors: R. Sfair, J. Boskovic, C. M. Schäfer, K. Trivedi

P31 - Secular dynamics of a coplanar, non-resonant planetary system, consisting of a star and two planets by Vladislav Sidorenko[1]

[1] Keldysh Institute of Applied Mathematics RAS

We consider an exoplanetary system consisting of a star and two planets. The masses of the planets are significantly less than the mass of the star, and there are no resonances of mean motions. The evolution of the orbital motion of exoplanets due to their mutual attraction is studied within the framework of a double averaged unrestricted three-body problem. The main attention is paid to coplanar configurations, when the star and planets move in a certain plane that preserves a constant position. Various variants of secular evolution are described in detail. In particular, the possibility of reversing the orbital motion of the inner planet is noted. Also we analyzed apsidal resonances representing stationary solutions of the averaged motion equations in which the positions of the lines of the apsides of the planets' orbits coincide. Bifurcation diagrams are constructed that characterize the dependence of the number of stationary solutions and their stability properties on the values of the problem parameters. The realization of apsidal resonances in real exoplanetary systems is discussed.

P32 - Chaotic diffusion in the GJ 876 exoplanetary system by Raphael Alves Silva[1]

[1] University of São Paulo

Chaotic diffusion is supposed to be responsible for instability scenarios in planetary dynamics, as a natural consequence of irregular motion. However, this is not always the case. In this work, we show that a resonant multiple-planetary system may exhibit irregular motion with low diffusion rates, leading to macroscopic instability times that are comparable to its host star age (order of Gyr). Our object of study is the Gliese 876 system, known to exhibit a Laplace resonant state involving its outer planets, in the ratios 4:2:1. We investigate the resonant dynamics through numerical simulations, and we measure the chaotic diffusion in the phase space applying the Shannon entropy approach, by exploring the planes of initial conditions of the three planets locked in the Laplace resonance. Hence, we are able to estimate the lifetime of the system, thus verifying that the resonance contributes to the system's long-term stability, even though the nominal condition lays within a hyper-chaotic domain, a scenario that is often called 'stable chaos'.

P33 - Search for the habitable worlds by their atmosphere characterization by Manika

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It is the most appropriate time to characterize the Earth-like exoplanets in order to detect biosignatures beyond the Earth because such exoplanets will be the prime targets of big-budget missions like JWST, Roman Space Telescope, HabEx, LUVOIR, TMT, ELT, HWO, etc. We provide models for the transmission and reflection spectra for the present and prebiotic (3.9 Ga) Earth-like exoplanets orbiting within the habitable zone of stars of spectral types F, G, K and M. Molecules that are potential biosignatures and act as greenhouse agents are incorporated in our model atmosphere. Various combinations of solid and liquid materials such as ocean, coast, land consisting of trees, grass, sand or rocks determine the surface albedo of the planet. Geometric albedo and model reflected spectra for a set of nine potential habitable planets, including Proxima Centauri b, TRAPPIST-1d, Kepler-1649c and Teegarden's Star-b, are also presented. We employ the opacity data derived by using the open-source package Exo-Transmit and adopt different atmospheric Temperature-Pressure profiles depending on the properties of the terrestrial exoplanets. We also calculated the phase curves of albedo and disk-integrated polarization by using appropriate scattering phase matrices and integrating the local Stokes vectors over the illuminated part of the disks along the line of sight. For this, we solve the 3D vector radiative transfer equations numerically. We present the effects of the globally averaged surface albedo on the reflection spectra and phase curves as the surface features of such planets are known to significantly dictate the nature of these observational quantities. Synergic observations of the spectra and phase curves will certainly prove to be useful in extracting more information and reducing the degeneracy among the estimated parameters of terrestrial exoplanets. Thus, our models will play a pivotal role in driving future observations.

P34 - Study of Long-term evaluation of space objects at High Area-to-Mass ratio in Geostationary orbits (GEO) by Shafeeq Tealib[1]
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This work simulated the long-term evaluation of space objects with a High Area-to-Mass ratio in Geostationary orbits (GEO) with a numerical propagator including all relevant perturbations. The JSC Vimpel catalog (http://spacedata.vimpel.ru) was used and compared with the results from the numerical propagator, to investigate the behavior of long-term dynamical space debris. Some results showed coincide our numerical propagator with that one data from the Russian catalog, while In some examples, there is a difference in the dynamical behavior between numerical integrators and data from the ephemeris. The interpretation of the results assures that space debris with a high area-to-mass ratio in GEO can remain in space for several decades with mean motion staying close to the original.

P35 - Terrestrial planet formation from a ring by Jason Man Yin Woo[1]
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It has been long proposed that, if all the terrestrial planets form within a tiny ring of solid material at around 1 AU, the concentrated mass-distance distribution of the current system can be reproduced. Recent planetesimal formation models also support this idea. In this study, we revisit the ring model by performing a number of high-resolution N-body simulations for 10 Myr of a ring of self-interacting planetesimals, with various radial distributions of the gas disc. We found that even if all the planetesimals form at $\sim$1 AU in a minimum mass solar nebula-like disc, the system tends to spread radially as accretion proceeds, resulting in a system of planetary embryos lacking mass-concentration at $\sim$1 AU. Modifying the surface density of the gas disc into a concave shape with a peak at $\sim$1 AU helps to maintain mass concentrated at $\sim$1 AU and solve the radial dispersion problem. We further propose that such a disc should be short lived ($\leqslant$ 1 Myr) and with a shallower radial gradient in the innermost region ($<$ 1 AU) than previously proposed to prevent a too-rapid growth of Earth.

P36 - Planetesimal and planetary embryo interactions in inclined binary star systems by Max Zimmermann[1]

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We investigate the dynamical evolution of a planetesimal and planetary embryo disk in an inclined S-type binary star configuration. In this setup the gas has already been dissipated, thus only gravitational interactions are taken into account. A disk of up to 2000 Ceres to Moon sized planetesimals and a few tens Moon to Mars sized planetary embryos is distributed between 1 and 4 au around the primary star. Previous computations have shown, that with time the disk objects are spread between 0° and $2 \times i_b$ where i_b is the inclination of the secondary star with respect to the primary-disk orbital plane. Thus, in this study we use the orbital parameters of an already evolved embryo/planetesimal disk and study the full gravitational interactions of the disk evolution for different binary star configurations. For the S-type binary star configurations we vary 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°) for two Solar-type stars. To compute all gravitational interactions, we use our recently developed GPU N-body code GANBISS, which is a highly parallelized implementation of the Bulirch-Stoer method on a GPU and can handle several thousand interacting objects in an S-type binary star configuration. We show a comparison with a prior investigation where the gravitational interaction of an initially cold disk has been studied. Special emphasis will be given to impact parameters between the various disk objects which are important for terrestrial planet formation.