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*

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.
References: 1. M.Zh. Minglibayev. Dynamics of gravitating bodies with variable masses and sizes [Dinamika gravitiruyushchikh tel s peremennymi massami i razmerami]. Lap Lambert Academic Publishing, 2012. ISBN 978-3-659-29945-2 (In Russian)
2. A.N. Prokopenya, M.Zh. Minglibayev, A. B. Kosherbaeva. Derivation of Evolutionary Equations in the Many-Body Problem with Isotropically Varying Masses Using Computer Algebra. Programming and Computer Software, vol. 48(2), pp.107–115 (2022). DOI: 10.1134/S0361768822020098
3. Nasa Exoplanet Archive, url: https://exoplanetarchive.ipac.caltech.edu/ (Last update: January 01, 2023)
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