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COMMISSION A4 CELESTIAL MECHANICS AND DYNAMICAL ASTRONOMY

TRIENNIAL REPORT 2021-2024

1. Background

The main goal of the IAU Inter-Division A-F Commission A4 "Celestial Mechanics and Dynamical Astronomy" is to co-ordinate and support the activities of IAU members working in these two broad fields. These activities include: treatments of the mathematical, physical and computational aspects of planetary theory, perturbation theory, resonance models, chaos and diffusion, stability criteria, orbital and space mechanics, ring systems, tidal models, galactic dynamics, non-gravitational forces, and computer languages for analytical developments.

In the triennial 2021-24, the number of members of the Commission A4 has raised to 213 (5% increase after the last (XXXI) IAU GA). The current geographical distribution of our members is: 117 members from Europe, 45 from North America, 29 from Asia, 14 from South America, 7 from Africa and 1 from Oceania. Particular on-going steps to increase membership were presented by the commission's president during the Division A meeting at the XXXI General Assembly.

One key feature of our Commission is its *interdisciplinarity*, owing to the fact that Celestial Mechanics and Dynamical Astronomy involves the application of the principles of the mathematical theory of dynamics in a wide spectrum of systems of astronomical interest, and it has historically served as a key element in the modelling and physical interpretation of such systems. The interdisciplinary character of our commission is manifest in the fact that, besides divisions A-F, most A4 members are members also on one or more of other IAU divisions and work in research areas where the analytical and numerical tools of celestial mechanics and dynamics are amply used. Thus, of our current 213 members:

- nearly all (206) are members of Division A (Fundamental Astronomy);
- about 72% (154) are members of Division F (Planetary systems and Astrobiology);
- about 30% (63) are members of Division B (Facilities, technologies and Data Science).

Many of these members participate in commissions or research activities related to observations, the definition and updating of standard IAU-adopted reference frames, and astrometry. However, there is an increasing number now involved also in developments

in data science. This includes, for example, the use of machine-learning methods in the processing of data derived from large observational campaigns, and the use AI tools in the dynamical modelling of astronomical systems. This trend shows that, side by side to the traditional methods of celestial mechanics (perturbation theory, study of resonances, stability and chaos), the general tendency of machine-learning and data science tools to now permeate all aspects and activities in astronomy has deeply affected also the research areas referred to by the activities of our commission.
- about 15% of our members participate in one or more commissions of, typically both, divisions H (interstellar Matter and Local Universe), and J (Galaxies and Cosmology). Most commonly, these are commissions related to observations and/or modelling of dynamical processes taking place in our Galaxy or in other galaxies (stellar dynamics, resonances, bar and spiral patterns and pattern speeds, galactic satellites, galactic tides and tidal streams, migration, secular evolution, dark matter haloes, black hole dynamics and dynamics in the centers of galaxies etc.,)
- 17 are members in Divisions D (High Energy Phenomena and Fundamental Physics), 4 in Division E (Sun and Heliosphere), and 26 in Division G (Stars and Stellar Physics). Note that the corresponding areas involve mostly non-gravitational dynamical processes in astrophysics, as, for example, particle motions in astrophysical magnetic fields, pulsations of stars, gas and accretion thereof, etc., where the notions of dynamical astronomy apply equally well.

2. Developments and events within the past triennium

With modern space missions, Celestial Mechanics has passed to a new era where the predictions about the motions of celestial bodies as well as orbit determination can be probed through high precision astrometric experiments or in-situ observations.

An important example of the advent of this new era is the DART (Double Asteroid Redirection Test) planetary defense mission, which aimed to test the possibility of deflection of an asteroid by a kinetic impactor. On September 26, 2022, the DART kinetic impactor collided with the secondary moon Dimorphos of the NEO asteroid Didymos. The impact caused a change of the orbital period by about 32 minutes, a fact due to the large $\beta-$ factor, i.e. ratio of linear momentum transferred to the asteroid by the impact over the transfer predicted for a plastic collision. Besides the orbit, the kinetic impact causes a series of effects, which will be probed by the DART-succeeding ESA's HERA mission, to be launched in October 2024, aiming to visit the binary asteroid and measure in detail its post-impact state. Among other information (related to the physical/geological properties as well as post-collision re-shaping of Dimorphos) the HERA mission will explore the new spin-orbit state of the Didymos-Dimorphos system. This state can deviate considerably from the one of the synchronous state under Keplerian orbit, owing to the triaxiality of Dimorphos, which implies that the kinetic impact excites a librating state that can be influenced both by secondary resonances and by chaos effects. Thus, the Didymos-Dimorphos system provides a great laboratory for testing several theories in Celestial Mechanics. It is noteworthy that the DART mission fueled itself important advancements in astrodynamics, related to mission design and the autonomous navigation of space probes.

Another example of the impact of high-precision data to the development of dynamical astronomy is the GAIA set of data releases. The early EDR3 set, originally released in 2020, was supplemented with substantial new information on June 2022 (DR3). the DR3 set contains now a wealth of new information on about 1.6 billion sources (galactic and extragalactic stars, galaxies and galaxy candidates, planetary transists, Solar System

small bodies etc.). Besides photometric and physical (spectral) properties of the observed objects, the 2022 release contains important information of use in the dynamical modelling both of our galaxy and of the closed environment of the observed objects, such as the radial and rotational velocities of stars, the definition of the celestial reference frame through the Gaia-CRF3 sources etc. Such data create unique chances for answering long-standing questions in astronomy, such as the precise mapping of the galactic potential, the value of pattern speeds of various non-axisymmetric structures in the galaxy, the shape and mass distribution of the dark matter halo etc. In essence, this implies a transfer of high precision understanding of gravitational systems from the solar system to the galactic scale.

Our commission members participate in activities, conferences and events of international character in all the above areas. In the sequel we report the main developments in the commission's area of activity during the last three years, including events supported by our commission and other ones of major international character.

2.1. *Events supported by the Commission*

1. The IAU Symposium 364 on "Multi-Scale (Time and Mass) Dynamics of Space Objects" was held in dual form in Iasi, Romania, from October 18 to 22, 2021. The Symposium was proposed by the previous organizing committee (2018-2021, President: A. Celletti) in 2019, but it was postponed due to the COVID events. The symposium was a major event which gathered together about 200 participants, out of whom 98 speakers (20 invited). A detailed description is provided in Commission A4 2021 Annual report.

2. One of the main goals of the IAU Commission A4 is to "promote the periodic holding of a Summer School aiming to train young researchers on the most important current topics in Celestial Mechanics and Dynamical Astronomy. Such schools can take place before major scientific meetings, such as the celebrated CELMEC conferences." In 2022, the Advanced Study School on "Celestial Mechanics -Theory and Applications" (CELTA ASI) 2022 was held from 15 to 27 August 2022 at Inverness & Skye, Scotland. The school was under the patronage of the IAU Commission A4, and included lectures by 16 invited speakers. The school was organized jointly with the 77th Scottish Universities Summer School in Physics, under the direction of Prof. Bonnie Steves (Glasgow Caledonian University, Vice-President of the Division A).

2.2. *Other events*

3. The Eighth International Meeting on Celestial Mechanics (CELMEC VIII) took place at the University of Rome Tor Vergata during the period 5-9 September 2022 (Organizing/Scientific committee: A. Celletti, G.F. Gronchi, C. Lhotka, U. Locatelli, G. Pinzari, S. Terracini). The format was hybrid, and there where 203 participants, including 24 invited talks. Two topical collections on i) "Innovative computational methods in Dynamical Astronomy" (editors: C. Lhotka, G.F. Gronchi, U. Locatelli, A. Celletti), and ii) "Variational and perturbative methods in Celestial Mechanics" (editors: A. Jorba, S. Teraccini, G. Pinzari, A. Celletti), including many original papers on developments presented at the conference, were published through the international journal "Celestial Mechanics and Dynamical Astronomy".

4. The joint Kavli-IAU symposium 382 on "Complex Planetary ststems II" was held in Namur from July 3 to 7 2023. The symposium hosted about 20 invited talks, and 55 more regular talks organized in eight sessions (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), as well as two roundtable discussions on Space Awareness and on Exoplanet Habitability.

Finally, let us mention that the past president (2018-2021) of the commission A4, and advisor for the 2021-2024 period, Prof. Alessandra Celletti, was recipient of the prestigeous D. Brouwer Career Award by the Division on Dynamical Astronomy of the American Astronomical Society for the year 2023. The award was to "recognize and celebrate her outstanding contributions to the advancement of KAM theory and to the study of regular and chaotic dynamics of Earth's satellites and space debris".

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President of the Commission