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COMMISSION D1 GRAVITATIONAL WAVE ASTROPHYSICS

Astrophysique des Ondes Gravitationnelles

PRESIDENT **Peter Shawhan**
VICE-PRESIDENT **Monica Colpi**
PAST PRESIDENT **Marica Branchesi**
ORGANIZING COMMITTEE **Ajith Parameswaran** *(Secretary)*, **Masaki Ando, Martin Hendry, Shannon Ryan, Eleonora Troja, Marta Volonteri**

TRIENNIAL REPORT 2021-2024

1. Background

IAU Commission D1 was created in 2015 with the goals of integrating gravitational-wave (GW) observations into mainstream astronomy, expanding the knowledge and science impact of GW astrophysics to the IAU community, and fostering communication among diverse communities. It brings together scientists involved in searching for, detecting, modeling and interpreting GW signals over 12 orders of magnitude in frequency—from nanohertz using Pulsar Timing Arrays, from millihertz to $\lesssim$1 Hz with space-based detectors, and from $\sim$10 Hz to kHz using ground-based detectors—with many connections to high energy phenomena and fundamental physics, the domain of Division D. Observing the Universe across the entire GW bandwidth will provide a quantum leap in our knowledge of the Universe, its constituents and of the laws of Nature.

As of 2024, IAU Commission D1 has approximately 230 members from over 30 countries.

The President of Commission D1 also serves *ex officio* as a member of the Gravitational Wave International Committee (GWIC), a organization dedicated to cooperatively developing the construction and coordinating the operation of current and future GW detection facilities. In this way, the global community of astronomers and astrophysicists embodied in the IAU maintains contact with the expanding GW detection capabilities.

2. Highlights in Gravitational Wave Astrophysics 2021-2024

In June 2023, multiple Pulsar Timing Array (PTA) collaborations from around the globe announced strong evidence for low-frequency GWs in the nanohertz frequency range, detected via careful measurements of the arrival times of pulses from 179 radio pulsars (Reardon *et al.* 2023, Agazie *et al.* 2023, Xu *et al.* 2023, Antoniadis *et al.* 2023). While earlier results had shown correlated variations in the arrival times from pairs of pulsars, the data accumulated over many years finally revealed a systematic dependence on the angular separation between pulsars, consistent with the expectation from a stochastic

background of gravitational waves permeating the universe. This long-anticipated finding opened a new front on direct detection of gravitational waves and a new view of the astrophysics of supermassive black hole binaries in galaxies.

This triennium saw the publication of numerous observational results from the O3 observing run of the ground-based LIGO-Virgo-KAGRA (LVK) detector network, which had ended data-taking in early 2020. The release of the GWTC-3 catalog update (Abbott *et al.* 2023a) by the LVK collaborations brought the number of detected GW events (and probable candidates) in the catalog to 90. This enabled many studies of the population and astrophysics of compact binary mergers, tests of general relativity, and cosmology measurements by the LVK collaboration and by other researchers. The GW strain data from the full O3 run was released through the Gravitational Wave Open Science Center (GWOSC) (Abbott *et al.* 2023b) which enabled the broader community to identify additional compact binary merger candidates and also to search for continuous-wave and other types of GW signals, complementing the searches for a wide variety of possible GW signals published by the LVK, some in partnership with other astronomers. The first science observations of the KAGRA detector in Japan, in coincidence with GEO 600, were published (Abbott *et al.* 2022). The O4 observing run of LVK detectors commenced in May 2023 and is ongoing.

Among the space-based GW missions under development, the LISA mission completed its conceptual and preliminary design phases and, in January 2024, reached a major milestone with successful reviews and the formal adoption of the mission by the European Space Agency (ESA). LISA is made possible by the collaboration between ESA, its Member State space agencies, NASA and an international consortium of scientists. Following adoption, the mission has now begun an implementation phase which is expected to lead to launching the three-satellite constellation in the mid-2030s. That will open a new observational window for massive black holes and their interactions, Galactic binaries, and other astrophysical sources (Colpi *et al.* 2024).

Planning for the next generation of ground-based GW detectors advanced greatly during this triennium. In Europe, the Einstein Telescope (ET) (Punturo *et al.* 2010, Branchesi *et al.* 2023) project was added to the European Strategy Forum on Research Infrastructures, an important step for recognition and future funding. Technical development and evaluation of candidate sites for the ET interferometers have proceeded with increasing activity, engaging a collaboration with over 1200 members. In the U.S., the Cosmic Explorer (CE) (Evans *et al.* 2021) project completed a "Horizon Study" and received funding from the National Science Foundation for conceptual design studies. Intense activity is ongoing in the formulation and presentation of the science with ET, and synergies with CE and other observatories, by the ET Observational Science Board and its members, with the plan to produce a "blue book" by the end of the year. Once they are built, these new detectors will have superb fidelity for many GW sources and also will make it possible to trace the cosmic star formation history, back to the cosmological dark ages, detecting the gravitational wave signal from millions of merging compact binaries. Joint electromagnetic observations of merging neutron stars will be numerous, and will shed light on the state of matter at supra-nuclear densities, the production of the heaviest elements in the Universe and the deep link of the sources with short GRBs.

3. Commission D1 Activities 2021-2024

IAU Symposium 363, "Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution", had been organized and supported by the Commission D1 Organizing Committee in the previous triennium but was postponed due to the

Covid-19 pandemic. It was ultimately held 29 November to 3 December 2021 using a virtual meeting platform, and successfully brought together astrophysicists, computational and nuclear physicists, and gravitational-wave researchers to discuss new findings and prospects in neutron-star astrophysics.

At the 2022 IAU General Assembly in Busan, Republic of Korea, gravitational wave astronomy and astrophysics figured significantly in the Division D meeting, with the theme "Across the Mass Spectrum of Neutron Stars and Black Holes", and in a Working Group meeting on Global Coordination of Ground and Space Astrophysics. The Korean Gravitational Wave Group, with support from the KAGRA Scientific Collaboration, organized and staffed a GW astronomy exhibit at the General Assembly which featured many aspects of GW and multi-messenger astronomy.

The Commission D1 Organizing Committee (OC) met periodically to share information from different segments of the GW science community, and to discuss issues of international scope. One outcome from those discussions was a decision to create a list of conferences and meetings related to GW Astrophysics on the IAU website, which the OC is actively maintaining as a resource for the community at https://iau.org/science/scientific_bodies/commissions/D1/info/meetings/. The OC also created a "Useful Resources" web page with links to online educational and reference materials for GW astronomy and astrophysics.

The OC offered support and advice to the team proposing an IAU Symposium on Gravitational Wave Astrophysics, and were delighted when the proposal was accepted as one of the Symposia in the 2024 IAU General Assembly in Cape Town, South Africa. It will be a wonderful exploration of all that gravitational waves have to offer to astronomy and astrophysics research.

4. Conclusion and future plans

Building on the first remarkable discoveries, the gravitational wave science community is providing a new view of our Universe that complements the more established observational methods. But the field continues to change rapidly, with improvements to current facilities and data sets, and ambitious, maturing plans for new facilities which will dramatically extend the reach of GW observations. The IAU's Commission D1 will continue to support this growing community and foster the strong international connections which are especially valuable for GW observations. Following the broad IAU Symposium 389 on Gravitational Wave Astrophysics, we can anticipate future meetings focusing on various intersections of GW and traditional astronomy and the astrophysical insights they will enable. With LISA and next-generation terrestrial interferometers coming online near the end of the next decade, Commission D1 will sustain those initiatives focussed on topics related to the joint analysis of the complex incoming data streams.

Peter Shawhan
President of the Commission

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