LISA Canada White Paper (2021)

A Synopsis of the 2021 LISA Canada Workshop
https://meetings.triumf.ca/event/220/
27-29 April 2021

1 Executive Summary

The LISA space mission will unlock a unique band of gravitational-wave observations, allowing new insight into stellar remnants at vast distances, novel probes of fundamental physics and cosmology, and tests of general relativity with unprecedented precision. In preparation for LISA to fly in the mid-2030s, Canadian researchers organized the 2021 LISA Canada Workshop to encourage pan-Canadian coordination of LISA research, to gauge the interest of Canadian physicists, astronomers, and industrial companies in contributing to the LISA mission, and to provide an introduction to ongoing LISA research and the LISA Consortium.

The LISA Canada Research Community: At the time of writing, 25 researchers in Canada, including 12 at faculty-level at nine Canadian institutions, are members of the LISA Consortium[1]. Prior to the 2021 LISA Canada Workshop, coordination of efforts among these researchers was infrequent. One of the workshop's main objectives was to create connections between these teams and establish a critical mass around which LISA efforts in Canada can be coordinated. In this regard, the workshop was highly effective, beginning to establish a robust new communication network across Canada for LISA research:

- A total of 108 Canadian researchers registered for the LISA Canada 2021 workshop, from 30 different Canadian institutions.
- In a post-workshop survey, 100% of Canadian respondents who were not already members of the LISA Consortium indicated they would like to join.

These researchers currently work in wide array of disciplines, including gravitational-wave astronomy with ground-based detectors such as LIGO and Virgo; cosmology; extreme stellar environments and stellar history; galaxy formation; modeling sources of gravitational radiation; tests of general relativity and theoretical explorations of extreme spacetime; particle physics and tests of dark matter; and experimental subatomic physics, among others. The LISA mission has the potential to leverage interdisciplinary expertise across Canada on a large scale, and Canadian scientists are prepared to rise to the challenge.

Partnering with Space Agencies and Industry: During the workshop, current leaders of the LISA mission and LISA Consortium gave an overview of the LISA mission, its scientific potential, and the current activities of LISA working groups. The workshop gave researchers who are new to LISA a pathway for entry into contributing to the Advocacy and Outreach, Astrophysics, Cosmology, Data Challenge, Data Processing, Fundamental Physics, Simulation, and Waveform working groups. Participants from the European Space Agency (ESA) and the LISA Consortium also discussed opportunities for Canada to contribute hardware to the LISA mission and established a line of communication between the workshop organizers, ESA, and the Canadian Space Agency (CSA) to identify potential overlap between the LISA mission needs and Canadian industrial expertise. Workshop attendees also identified computing infrastructure (hardware and software) as a potential contribution to the LISA mission where Canada has considerable experience and expertise.

Looking Ahead In post-workshop survey results, Canadian researchers expressed interest in future semi-annual LISA Canada meetings as well as collaboration on proposals to fund LISA-related research. Canadian

[1]Canadian LISA Consortium members are currently based at Bishop's University, University of British Columbia, University of Guelph, University of Lethbridge, McGill University, Perimeter Institute, TRIUMF, University of Waterloo, and York University.

respondents also identified guidance from the LISA Consortium and funding for highly qualified personnel (HQP) trainees as the resources most needed in order to contribute to LISA science.

2 The LISA Mission

The Laser Interferometer Space Antenna (LISA) is a space-based gravitational wave (GW) detector sensitive to gravitational waves with frequencies between roughly 0.1-100 mHz [1]. LISA will consist of three satellites in heliocentric orbit arranged in an approximately equilateral triangle. The spacecraft, separated by about 2.5×10^6 km from each other, each contain two test masses that float freely inside the spacecraft and are essentially in free fall. Micro-thrusters and monitoring equipment cause the spacecraft to follow the motion of the test masses, which experience negligible relative motion other than that due to gravity. Gravitational waves passing through the array will stretch spacetime, and modulate the relative distances between the test masses at the picometer level. These changes in distance between the test masses in different spacecraft are measured using laser interferometry. Each spacecraft sends a laser beam towards the other two spacecraft through 30 cm telescopes, and in return receives incoming laser light from the other spacecraft. These beams are brought to interference with beams bounced off of the test masses and combined in photodiodes, which measure the changing interference of the beams as the gravitational waves modulate the distances. Measurements of the lengths of the three arms, in both directions, are combined to suppress technical noise and construct a time series representing the gravitational-wave strain in the two orthogonal polarizations (rotated by 45 degrees).

LISA's frequency band (roughly 1 mHz to 1 Hz) will make it sensitive to lower frequency sources of gravitational radiation that cannot be studied with terrestrial experiments such as LIGO or Virgo. This will allow the detection of radiation from much more massive sources. Particularly exciting sources are mergers of supermassive black holes, massive compact binary systems in the Milky Way, extreme mass ratio inspirals (stellar mass compact objects orbiting the massive black holes in the centres of galaxies), and possibly stochastic gravitational wave backgrounds. LISA will detect massive black hole binary mergers out to redshifts of 15, yielding new insights into the formation history of black holes that seed galaxy formation. Binary sources may be seen in LISA years before they coalesce and are detectable by terrestrial GW detectors, which will allow precise sky localization astronomers can use to target electromagnetic counterparts. Stellar black hole binaries and extreme mass ratio inspirals serve as standard sirens of known strength that can be used to measure the Hubble expansion parameter h ultimately to a precision of 0.02, with systematics that are completely different from those of present measurements. Detections of sources by LISA will permit precision tests of general relativity and fundamental physics. LISA is well-aligned with the Canadian Astronomy Long-Range Plan for 2020-2030 [2]. This report placed high priority on multi-messenger astronomy, including gravitational waves. Canadian involvement in LISA would leverage highly-ranked observatories, including the CSA's CASTOR mission, as well as CFHT/Gemini, SKA, ngVLA, LSST/Rubin Observatory, and the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD).

LISA is scheduled for launch in the mid-2030s. The LISA mission is currently expected to conduct 4 years of observation, with a potential extension to 10 years. The European Space Agency leads the mission, with significant contributions from NASA and from the LISA Consortium — an international group of researchers interested in contributing to LISA's scientific program.

3 LISA in Canada and the LISA Canada workshop

Current Canadian participation in LISA involves researchers from across the country working in a wide range of disciplines. As of June 2021, there were 12 faculty-level members and a total of 25 researchers from Canadian institutions registered as official members of the LISA Consortium. This effort can be classified loosely along four main lines of inquiry. The first involves scientists who are already doing gravitational wave astronomy through the LIGO Scientific Collaboration. Their direct experience in building, running, and analyzing data from gravitational wave detectors will provide crucial guidance for the LISA mission. A second group comes primarily from the Canadian astronomy community (CASCA) and whose interests in extreme stellar environments and cosmology connect with the unique detection capabilities of LISA. This community itself is very diverse and brings a wide range of expertise, including work on space-based projects in collaboration with the CSA. The third direction is mainly theoretical and involves researchers studying sources and waveforms of gravitational radiation based on gravity in the strong field regime, deviations from its description in terms of general relativity, and potential signals from new cosmological phenomena. This group explores important science targets for LISA and connects in important ways with the Fundamental Physics, Cosmology, and Waveform LISA Working Groups. And fourth, a growing interest in the LISA mission is developing within the Canadian subatomic physics experimental community. These researchers bring significant experience and skills in advanced detector development, data analysis, and running large scientific collaborations.

The first-ever LISA Canada Workshop was held over April 27-29, 2021, organized by current members of the LISA Consortium in Canada. The primary goal of the workshop was to develop a strong and connected LISA community in Canada. As part of achieving this goal, the workshop aimed at attracting new researchers to LISA, and sought to highlight the many ways in which people can get involved in the mission. The workshop featured talks by key members of the major LISA working groups that emphasized the enormous scientific potential of the mission as well as its timeline and organizational structure. The workshop also presented current LISA-related science by researchers in Canada. Attendance at the workshop included over 300 registrants, with about a third of these currently based at Canadian institutions. This participation spanned a broad range of researcher backgrounds, career levels, and institutions, and also included representatives from industry and the CSA. A survey was shared with workshop participants after the event. Feedback on the workshop was very positive; 100% of Canadian researchers who responded to the survey who were not already members of the LISA Consortium indicated interest in joining. Most Canadian researchers who responded indicated interest in future semi-annual LISA Canada meetings, and roughly half indicated interest in exploring the formation of a federated LISA Canada group, advocacy for funding LISA efforts within Canada, and collaboration on funding proposals. Canadian survey respondents identified guidance from the LISA Consortium and funding for HQP trainees as the resources they would most need in order to contribute to LISA science.

4 Opportunities for Canadian involvement in LISA

LISA is organized into two parts: the LISA Mission, led by the European Space Agency (ESA), and the LISA Consortium. The mission includes the three spacecraft, launch vehicle, ground support, and many aspects of the instrument hardware. The LISA Consortium, representing academic researchers, consists of two subgroups. One of these focuses on instrumentation and data processing, while a second group studies science deliverables, and contains within it subgroups focused on astrophysics, cosmology, fundamental physics, GW waveform modelling, and data analysis techniques. The LISA Canada workshop featured talks from all of these groups, and we summarize here some of the opportunities for Canadian involvement that have been identified.

4.1 Potential hardware opportunities

Hardware contributions to LISA offer one possible avenue for the Canadian scientific and space industry communities to participate in this upcoming ESA flagship mission. Canada supports a healthy space industry ecosystem with both large and small industrial partners, and the Canadian Space Agency has extensive expertise in connecting missions with these highly-qualified industrial partners. These partners, in turn, offer expertise in working with the CSA, ESA, and NASA to develop and execute space-enabled instrumentation. A few examples of successful previous partnerships include a cryogenic scanning mirror mechanism contributed by ABB to the ESA-led SPICA mission, and upcoming contributions by Nüvü Cameras (in partnership with ABB) to NASA's Nancy Grace Roman Space Telescope. Workshop attendee Sarah Gallagher (CSA Science Advisor) noted that since the LISA mission has the unique requirements of a gravitational wave interferometer, a broad new swath of prospective Canadian industrial partners may be interested in contributing. The CSA is well poised to make new connections between technology requirements and Canadian industrial capacity.

Specific hardware contributions with potential for development and testing within the Canadian space industry sector must first be identified by the European Space Agency in consultation with its primary partners, *e.g.*, during the ongoing LISA Phase A study (ending circa December 2021). Contributing workshop attendees Martin Gehler (ESA) and Martin Hewitson (LISA Consortium) will be on the look-out for contribution opportunities and will alert workshop organizers should these arise. The Canadian Space Agency operates via Requests For Information (RFI) and Space Technology Development Programs (STDP), the latter of which are funded, and CSA-supported contributions would need to be developed through and competed in these processes. Successful collaborations of this type (e.g., between university, industrial, CSA, and international partners) have historically had a Canadian champion (or champions) who organizes and leverages Canadian scientific and technological expertise. One objective arising from the 2021 LISA Canada Workshop is the identification of individuals who will provide this motive force and liaise with the CSA and ESA to advance technology development opportunities.

4.2 Data processing and simulation

The LISA Data Processing Group (LDPG) coordinates the Consortium's contributions to define, develop and operate the LISA Science Ground Segment, which comprises the mission operation centre and the science operation centre. The main activities include prototyping of data-analysis algorithms (*e.g.,* instrument performance simulators and the initial noise reduction pipeline), providing support for various consortium tools and product quality assurance, and defining and organizing the Distributed Data Processing Centre.

The Simulations Working Group, a part of the LDPG, maintains a detailed simulation of the response of the LISA instrument, including effects such as orbital motion of the spacecraft, laser frequency offsets and fluctuations, and clock jitter. These are used to model instrumental noise sources affecting the measurement. A particular challenge is to model transient glitches as seen in the LISA Pathfinder.

The LISA Data Challenge (LDC) working group establishes various software-development standards and provides a common playground to evaluate different data-analysis algorithms. It also works closely with the data processing working group and the science working group to develop end-to-end data-analysis pipelines. So far two rounds of mock data challenge tasks ("Radler" and "Sangria") have been issued with increasing complexity in instrumental noise assumptions and source realization. Fifteen submissions from research groups worldwide have been received, searching for different types of sources (massive black hole binaries, galactic white-dwarf binaries, etc.) within the "Radler" data. Future challenge tasks will address the issues associated with non-stationary instrumental noise and test the global fit solutions for overlapping source waveforms within the same data steam.

There are promising opportunities for Canadian researchers to make contributions to the LISA data processing, simulation, and data challenge efforts, as discussed in the invited and breakout sessions. The consortium has strong demand for computing power and software engineering for the LISA mission, so that siting a LISA computing centre in Canada becomes an attractive option. Considering Canadian infrastructure and cutting-edge research in fundamental and applied research in scientific and quantum computing, such demand may represent a valuable opportunity for Canada to acquire a leading role in aspects of LISA data processing. Canadian researchers are also encouraged to participate in the data-analysis projects and contribute to science developments at all levels.

4.3 Astrophysics and waveform modelling

The Astrophysics Working Group (AstroWG) is the largest in the consortium and has a number of different topics in its purview including identifying and forecasting the numerous source populations, understanding how different astrophysical processes will be imprinted on the observed gravitational wave signals, and coordinating efforts with other observatories in order to do multi-messenger astronomy (*i.e.* combining electromagnetic and gravitational wave observations). LISA will target gravitational wave sources like merging binary black holes that will be qualitatively similar to those seen by ground-based detectors like LIGO/Virgo but that radiate GWs at much lower frequencies. LISA will also target a range of new sources, such as white dwarf binary stars in our own galaxy or compact objects orbiting supermassive black holes that are roughly a million times larger in mass (known as extreme mass ratio inspirals). As LISA will be a new instrument operating in a previously unexplored frequency band, the possibility of detecting unanticipated "surprise" sources is particularly exciting.

The Waveforms Working Group (WavWG) is charged with developing templates for all of these different signals. The diversity of sources means that a number of different methods will need to be combined in developing waveforms, including analytic techniques from black hole perturbation theory and supercomputer simulations from numerical relativity, and this varied expertise is reflected in the leadership and membership of the group. The long timescales of the signals, some of which can last months, as well as the extremely high signal-to-noise ratio, place very stringent demands on the waveform models in order for theoretical errors not to dominate over experimental uncertainties. This poses a great challenge that will require a community-wide effort in the lead-up to LISA's launch.

The Astrophysics and Waveform working groups are seeking to build up collaboration and address these outstanding goals through regular meetings and flagship projects. There is ample opportunity for Canadian institutions to contribute to these efforts, as several groups have expertise in the above areas, including analytical waveform modelling, numerical relativity, and multi-messenger observations. We heard about several examples of this already happening during the parallel sessions highlighting Canadian researchers, including following up gravitational wave events with Canadian telescopes, efforts to calculate extreme-mass-ratio waveforms using perturbative techniques, and research incorporating "environmental effects" (e.g., the presence of an accretion disk) into models of these systems.

4.4 Cosmology and fundamental physics

The potential scientific discoveries of LISA in fundamental physics, cosmology, and particle physics are very promising, and have attracted many studies in recent years. A number of Canadian LISA members are members of the Cosmology and Fundamental Physics Working Groups (CosWG, FPWG), and have contributed to a review article presenting scientific opportunities in LISA [3]. There are several directions along which the LISA mission can offer deep insights into these fields. Among them are the study of individually-resolved mergers of binary objects, which can provide signatures of cosmological, particle physics, and quantum gravity effects, and the search for the stochastic GW background, which could allow the study of cosmology beyond the last scattering surface.

By analyzing the mass and spin distributions of the population of black holes, LISA can study the effects of black holes superradiance, stellar cooling and black hole formation, and the possible primordial origin of some of the observed black holes. Analysis of the luminosity distance of mergers through multi-messenger approaches enables one to use black holes as standard sirens for an independent measurement of the Hubble parameter H_0. The study of the waveforms produced by compact objects can be used to study the interior of black holes, the fine structure of spacetime such as the scale of possible breakdown of Lorentz symmetry, and the imprint of the quantum nature of spacetime on the propagation of gravitational waves.

Another pathway to fundamental physics discoveries is the search for stochastic backgrounds of GWs. LISA is expected to measure the astrophysical contributions from binary mergers of black holes and galactic white dwarfs. This could lead to the discovery of a primordial background, which is predicted in many scenarios beyond the Standard Model of particle physics and/or the standard ΛCDM cosmological model. LISA will also be able to test for various dark matter candidates, and test for cosmological scenarios such as phase transitions in the early Universe.

The detection of a primordial GW background would also offer an uncontaminated window into the earliest stages of cosmological history, with the potential for studying further properties such as the presence of new particles and modifications of cosmological history. In particular it could lead to significant insights into the quantum epoch of the Universe beyond the surface of last scattering. LISA can also look for dark matter density spikes around compact objects and black holes. Due to gravitational effects, a local higher density of dark matter, called a spike, is expected to exist around compact objects. If another compact object orbits around the central one, then this spike creates a "friction" effect which leads to the orbiting object losing its energy not only due to emission of gravitational waves but also due to this friction effect. This leads to a modification of a purely general relativistic gravitational wave pattern that may be picked up by LISA [4, 5].

Many of the above topics were discussed at length in the LISA Canada Workshop. Participants in a breakout session panel discussion expressed what they see as the most exciting observations they hope to see in the first 4 years of LISA running: primordial stochastic backgrounds, standard sirens with electromagnetic counterparts, low-mass (multiband) inspirals, extreme mass ratio inspirals (in order to characterise Kerr black holes), quantum gravity effects in cosmological and black hole phenomena, and the possibility of a surprise measurement.

Research on the above topics and beyond is conducted by a number of Canadian groups, including at Bishop's, CITA, Guelph, McGill, Perimeter Institute, TRIUMF, and the Universities of British Columbia, Guelph, Lethbridge, Toronto, Trent, and York.

5 Conclusion

The LISA mission is poised to open up a new window to lower-frequency gravitational waves, which will probe mergers of a variety of stellar objects over a wide range of redshifts. Although Canada does not currently have official national involvement in the LISA mission, a number of Canadian researchers are already members of the LISA Science Consortium. The Canadian Space Agency and the Canadian space astronomy community are committed to upholding the priorities of the 2020 Canadian Long Range Plan *Discovery at the Cosmic Frontier* (LRP2020) [2] in which gravitational wave and multi-messenger science play an important role. (See for example LRP2020 white papers W024 [6], W031 [7], W034 [8], W036 [9], W041 [10] and W042 [11], which detail Canadian ambitions in high-energy and multi-messenger astrophysics.) Gravitational wave discoveries are also highlighted in Chapters 4 (observation) and 6 (theory) of this strategic report; contributions to the LISA Mission offer an unparalleled opportunity to meet these LRP objectives.

The 2021 LISA Canada workshop was a resounding success, attracting approximately 300 registrants (including a third from Canadian institutions). The key achievements of the workshop were:

- The workshop plenary sessions provided a broad overview of the LISA mission to Canadian researchers, and increased exposure of LISA science to these researchers. This was key to encouraging increased and new participation in preparatory LISA science from Canada.
- The workshop discussion sessions facilitated dialogue between the LISA leadership and Canadian researchers, enabling the exploration of possible official Canadian contributions to the mission. Furthermore, the workshop established points of contact both in Canada and the LISA collaboration for future pursuit of such endeavours.
- The organization of the workshop consolidated possible scientific collaborations between Canadian researchers who are interested in LISA. While previously interest in LISA was scattered across Canada with little collaboration, the dialogue from this workshop enabled Canadian researchers to pursue future collaborations in grant funding, HQP co-supervisions, and science.

Future directions for Canadian scientists interested in LISA include:

- Increased participation in the LISA Science Consortium ,through membership applications from researchers who were not already members
- Exploration of Canadian LISA hardware contributions, through continued dialogue between Canadian researchers, the CSA, and industrial partners
- Scientific collaborations on LISA preparatory science, in both theory and electromagnetic observations of LISA-detectable sources
- Exploration of a federated LISA Canada working group among Canadian researchers interested in LISA
- Organization of future semi-annual meetings on LISA-related efforts conducted by Canadian researchers.

References

[1] P. Amaro-Seoane *et al.*, "LISA Proposal", arXiv:1702.00786 [astro-ph.IM].

[2] Canadian Astronomical Society, "Discovery at the Cosmic Frontier: Canadian Astronomy Long Range Plan 2020-2030", https://casca.ca/?page_id=11499.

[3] E. Barausse, E. Berti, T. Hertog, S. A. Hughes, P. Jetzer, P. Pani, T. P. Sotiriou, N. Tamanini, H. Witek and K. Yagi, *et al.* "Prospects for Fundamental Physics with LISA", Gen. Rel. Grav. **52**, no.8, 81 (2020) doi:10.1007/s10714-020-02691-1 [arXiv:2001.09793 [gr-qc]].

[4] B. J. Kavanagh, D. A. Nichols, G. Bertone, and D. Gaggero, Phys. Rev. **D102**, 083006 (2020) [arXiv:2002.12811 [gr-qc]].

[5] G. Bertone et al, SciPost Phys. Core 3, 007 (2020). [arXiv:1907.10610 [astro-ph]].

[6] Hénault-Brunet, V., Bahramian, A., Côté, P., Eadie, G., Haggard, D., Harris, B., *et al.*, "Star Clusters Near and Far", LRP W024 (2019), doi.org/10.5281/zenodo.3758603

[7] Hoffman, K., Heyl, J., Caiazzo, I., Gallagher, S., Haggard, D., Jasiobedzki, P., *et al.*, "The Colibrì Mission: Canada's Flag-ship X-ray Telescope" LRP W031 (2019), doi.org/10.5281/zenodo.3765587

[8] Woods, T.E., Alexandroff, R., Ellison, S., Ferrarese, L., Gallagher, S., Gallo, L., Haggard, D., *et al.*, "Revealing the Origin and Cosmic Evolution of Supermassive Black Holes", LRP W034 (2019), doi.org/10.5281/zenodo.3765791

[9] Caiazzo, I., Belloni, T., Cackett, E., Damascelli, A., De Rosa, A., Dosanjh, P., *et al.*, "Unveiling the secrets of black holes and neutron stars with high-throughput, high-energy resolution X-ray spectroscopy", LRP W036 (2019), doi.org/10.5281/zenodo.3824441

[10] Fernandez, R., Bovy, J., Chen, A., Cumming, A., Cote, B., Davids, B., *et al.*, "The cosmic origin and evolution of the elements", LRP W041 (2019), doi.org/10.5281/zenodo.3824912.

[11] Ruan, J.J., Afsari, N., Brunner, T., Carlberg, R., Doyon, R., Drout, M., Dykaar, H., Fernandez, R., Gaensler, B., Haggard, D., Kaspi, V., Lafreniere, D., McIver, J., Moon, D.-S., Ni, Y.C., Safi-Harb, S., Spekkens, K., Tohuvavohu, A., Vieira, N., Virtue, C.J., "A Vision for Canadian Leadership in Multi-Messenger Astrophysics in the Next Decade", LPR2020 W042 (2019), doi.org/10.5281/zenodo.3825042.

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Appendix C: Potential funding sources for LISA efforts in Canada

- Arthur B. McDonald Institute
- Canada Foundation for Innovation (CFI)
- Canadian Space Agency Flights and Fieldwork for the Advancement of Science and Technology (CSA FAST)
- Natural Sciences and Engineering Research Council of Canada (NSERC)
- New Digital Research Infrastructure Organization (NDRIO)