Une version française de ce message apparaît sur la page suivante.

September 11, 2020

Dear colleagues,

We are pleased to present a public release of the first component of the Canadian Astronomy Long Range Plan 2020-2030 ("LRP2020"). This release contains two sections:

- Chapter 5: Recommendations on Facilities, Projects and Resources
- Chapter 6: Future Landscape

This release focuses on observational facilities, some of which have upcoming deadlines and decision points. Text from these Chapters on theoretical astrophysics, digital research infrastructure and instrumentation development is not yet complete, and will be released at a later date.

An overall timeline for the completion of the full LRP2020 report can be found on our webpage. We would be grateful for your assistance in pointing out any typographical or factual errors in this release (please respond by email to chairs@lrp2020.groups.io). Aside from any small corrections, we consider this to be the final version of the English text.

We are extremely grateful for the large volume of thoughtful feedback that we received on the community draft. Every comment received was discussed and considered, and almost all of this is now incorporated in the released document. We also express our gratitude to the members of the LRP2020 panel, who continue to devote enormous time to this process under challenging circumstances.

The released text is enclosed, and also available at https://casca.ca/wp-content/uploads/2020/09/LRP2020_Sep2020_release.pdf. This is now a public document, and can be shared with all audiences.

Pauline Barmby and Bryan Gaensler
LRP2020 Co-Chairs
chairs@lrp2020.groups.io

11 septembre 2020

Chers collègues,

Nous sommes heureux de présenter une version publique du premier volet des Plans canadiens à long terme pour l'astronomie 2020-2030 («PLT2020»). Notez qu'il n'existe actuellement qu'une version anglaise de ce document; une traduction française sera faite du rapport final. Cette version contient deux sections:

- Chapitre 5: Recommandations sur les installations, les projets et les ressources
- Chapitre 6: Paysage futur

Cette version se concentre sur les installations d'observation, dont certaines ont des dates limites et des points de décision à venir. Le texte de ces chapitres sur l'astrophysique théorique, l'infrastructure de recherche numérique et le développement de l'instrumentation n'est pas encore terminé et sera publié à une date ultérieure.

Un calendrier général pour l'achèvement du rapport complet PLT2020 est disponible sur notre page Web. Nous vous serions reconnaissants de votre aide pour signaler toute erreur typographique ou factuelle dans cette version (veuillez répondre par courriel à chairs@lrp2020.groups.io). Mis à part toutes petites corrections, nous considérons qu'il s'agit de la version finale du texte anglais.

Nous sommes extrêmement reconnaissants pour le grand nombre de commentaires réfléchis que nous avons reçus sur le projet communautaire. Chaque commentaire reçu a été discuté et pris en compte, et presque tout cela est maintenant incorporé dans le document publié. Nous exprimons également notre gratitude aux membres du panel PLT2020, qui continuent de consacrer énormément de temps à ce processus dans des circonstances difficiles.

Le texte publié est joint et également disponible sur https://casca.ca/wp-content/uploads/2020/09/LRP2020_Sep2020_release.pdf. Il s'agit désormais d'un document public et peut être partagé avec tous les publics.

Pauline Barmby et Bryan Gaensler
Coprésidents du PLT2020
chairs@lrp2020.groups.io

Chapter 5: Recommendations on Facilities, Projects and Resources

In this Chapter, we present priorities and recommendations for Canadian astronomy over the next decade. These include key overarching recommendations for the entire field, as well as specific recommendations in the areas of theoretical astrophysics, digital research infrastructure, instrumentation development, and observational facilities;[1] a summary of the corresponding funding requirements is provided in Table 1. These combined initiatives represent a vision for a flourishing and successful astronomical community that will have access to dramatic new capabilities across theory, experiment and observation, and which will sit at the forefront of knowledge and discovery. Specifically, the priorities we recommend in this report will deliver:

- powerful new observational facilities on the ground and in space;
- high-capacity computation facilities for both theory and data processing;
- the human capital and technological capacity needed to exploit these facilities and to thereby make fundamental advances across astronomy as summarized in Chapter 4;
- multiple international leadership positions for Canadian astronomers; and
- inclusive and respectful relationships within our community and with the communities in which we work.

Implementation of these recommendations will be overseen by the Long Range Plan Implementation Committee (LRPIC) of the Canadian Astronomical Society (CASCA). The status of these recommendations plus proposed updates or changes will be considered in a Mid-Term Review (MTR) to take place in around 2025.

[1] Further detailed discussion on theoretical, computational and observational priorities is provided in Chapter 6, while a wider set of recommendations on funding, governance, and the role of astronomy in Canadian society are discussed in Chapter 7.

Table 1: Recommended Canadian investments in observational facilities over the period 2021-2030. Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change. For further details, see the full discussion around each recommendation in Chapter 6 or Chapter 7.

RECOMMENDED GROUND-BASED FACILITIES: LARGE (>$30M) INVESTMENTS IN NEAR-TERM PROJECTS			
Priority	***Project***	***Anticipated Cost to Canada (New Construction / Operations)***	***Estimated Operational Date***
1	VLOT (TMT)[2]	TBD[3] / US$7M[4] per year	2033 or later
2	SKA1	Observatory: $80M[5] / $8M[6] per year SKA1 Regional Centre: $45M[7] (construction plus ops)	2026 (science verification)
RECOMMENDED GROUND-BASED FACILITIES: LARGE (>$30M) INVESTMENTS IN FUTURE PROJECTS (unranked)			
Project (alphabetical)		***Anticipated Cost to Canada (New Construction / Operations)***	***Estimated Operational Date***
MSE		$110M[8] / $7M[8] per year	2031
ngVLA		US$130M[8] / US$6M[8] per year	2028 (early science)
RECOMMENDED GROUND-BASED FACILITIES: CONTINUED MID-SCALE ($5M-$30M) INVESTMENTS IN CURRENT FACILITIES			
Priority	***Project***	***Anticipated Cost to Canada (Ongoing Operations)***	***Operational Since***
1	ALMA	US$1.8M[9] per year	2011
2	Gemini	US$6.0M[9] per year	1999-2000
3	CFHT	US$4.0M[9] per year	1979
(table continues on next page)			

[2] At the time of writing Canadian access to a very large optical telescope is best implemented by continued participation in TMT, sited either at Maunakea in Hawai'i or Observatorio del Roque de los Muchachos in the Canary Islands.
[3] In 2015, the Canadian government committed $243.5M for specific TMT activities, including NFIRAOS and enclosure construction. Any additional construction costs are not yet determined.
[4] The annual operations cost for TMT constructed on Maunakea vs TMT constructed on Observatorio del Roque de los Muchachos are similar to within a few percent.
[5] in 2017-dollars
[6] Average annual cost in 2017-dollars for 2021-2030 during the SKA1 construction phase, with costs ramping up towards the end of the decade.
[7] Cost for a Canadian SKA1 Regional Centre over 2021-2030 in 2017-dollars, including processing, storage, networking, and staffing costs.
[8] in 2018-dollars
[9] Canadian contribution in calendar year 2020

RECOMMENDED GROUND-BASED FACILITIES: NEW MID-SCALE ($5M-$30M) INVESTMENTS IN FUTURE FACILITIES			
Priority	***Project***	***Anticipated Cost to Canada (New Construction / Operations)***	***Estimated Operational Date***
1	CHORD	$23M / $0.6M per year	2023
2	CMB-S4 or comparable facility	$4M-$7M / $0.5M per year	2026
3	LSST	- / $3M per year (in kind)[10]	2023
RECOMMENDED SPACE ASTRONOMY MISSIONS: VERY LARGE (>$100M) INVESTMENTS			
Priority	***Mission***	***Anticipated Cost to Canada***	***Estimated Launch Time Scale***
1	CASTOR	$250M-$400M	late-2020s
2	NASA Flagships[11] (Hardware, Science, Technical)	~$100M	mid-2030s
RECOMMENDED SPACE ASTRONOMY MISSIONS: LARGE ($25M-$100M) INVESTMENTS			
Priority	***Mission***	***Anticipated Cost to Canada***	***Estimated Launch Time Scale***
1	LiteBIRD	$25M-$40M	late-2020s
2	SPICA	$30M-$50M	early-2030s
RECOMMENDED SPACE ASTRONOMY MISSIONS: OTHER (<$25M) INVESTMENTS			
Priority	***Mission***	***Anticipated Cost to Canada***	***Estimated Launch Time Scale***
1	JWST	TBC[12]	late 2021
2	POEP	$15M[13]	mid-2020s
3	NASA Flagships (Science, Technical only)	TBD	mid-2030s

[10] LSST is not accepting cash funds from its partners to cover operations. The amount listed is the cost of in-kind Canadian contributions to LSST operations.
[11] A hardware contribution to a NASA Flagship mission should be regarded overall as a lower priority than investing in LiteBIRD and SPICA at the recommended levels.
[12] Support for the operations phase over the nominal JWST mission lifetime of five years; does not include costs incurred so far.
[13] This does not include launch, which is expected to be a small increment on the total cost.

Recommendation on Selecting the Locations of Astronomy Facilities and Infrastructure

We recommend that the Canadian astronomical community (e.g., ACURA, CASCA and NRC-HAA) work together with Indigenous representatives and other relevant communities to develop and adopt a comprehensive set of guiding principles for the locations of astronomy facilities and associated infrastructure[14] in which Canada participates. These principles should be centred on consent from the Indigenous Peoples and traditional title holders who would be affected by any astronomy project. In addition, when such consent does not exist, the principles should recognize that the use of force is an unacceptable avenue for developing or accessing an astronomical site. The principles should also acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime. These principles should be developed as soon as possible, and then applied to *all* future Canadian participation in new or existing astronomical programs, projects and national and international facilities. Engagement and implementation should be consistent with the spirit of the Calls to Action of the Truth and Reconciliation Commission of Canada and of the United Nations Declaration on the Rights of Indigenous Peoples.

Recommendation on Coordination of Funding Agencies

We recommend that the leadership of agencies which fund or otherwise support astronomical research (NRC, CSA, CFI, NSERC, NDRIO, CIFAR) coordinate efforts through regular meetings. Involving ACURA and/or LRPIC in such meetings could further improve coordination efforts.

Recommendations on Theoretical Astrophysics

Not included in the September release.

Recommendations on Digital Research Infrastructure

Not included in the September release.

Recommendations on Instrumentation Development

Not included in the September release.

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[14] Astronomy projects not only require telescopes and observatories, but also need support facilities, headquarters, project offices, instrumentation laboratories, integration and test facilities, computing and processing centres, etc.

Recommendations on Observational Facilities

Canadian astronomy's strong record of success has come from our involvement in facilities with a broad range of project sizes, time scales, and science areas. No single telescope or program can answer the wide range of scientific questions set out in Chapter 4. To make fundamental discoveries and to provide outstanding training opportunities, Canadian astronomy will require investment and participation in telescopes and experiments both on the ground and in space, covering a range of wavelengths, technologies and science programs. We correspondingly recommend below a set of facilities that provide the full set of capabilities needed to explore the cosmos. These facilities provide Canadian leadership or substantial involvement across all wavelengths, using telescopes that have unique and distinct technical capabilities.

The recommendations below are based on a set of pre-defined criteria announced at the initiation of the Long Range Planning process. Scientific excellence is the first and most fundamental criterion: recommended initiatives must enable fundamental or transformational advances in our understanding of the Universe. An additional overall criterion is that the sum of the recommendations should provide a set of facilities and programs that reflects the strengths and breadth of Canadian astronomy, with a range of project sizes, time scales, science areas and degrees of Canadian participation, offering strong prospects for training of Canadian HQP, and providing specific tangible benefits to Canadians.

Optical/infrared/ultraviolet astronomy and radio/millimetre/sub-millimetre astronomy are the two broad pillars that have historically underpinned much of Canadian observational astrophysics. A key component of a world-class Canadian astronomy program is strength across both these spheres. Throughout the coming decade, we also anticipate that Canadians will contribute to and participate in major programs at X-ray and gamma-ray wavelengths, and across multi-messenger astrophysics and astroparticle physics.[15]

For **optical/infrared/ultraviolet astronomy**, Canada needs capabilities in both imaging and spectroscopy, and needs telescopes whose observations are both "wide" (able to cover large areas of the sky) and "deep" (able to study very faint objects). There also needs to be a pathway from surveys, which perform large censuses and uncover entire new populations of objects, to targeted individual observations, which study specific stars, galaxies and other phenomena in detail. Our recommended set of facilities provide all these capabilities:

- **Broad surveys:** The **CASTOR** space mission will provide a hundredfold improvement in survey speed over the Hubble Space Telescope, and will consequently allow Canadian astronomers to perform spectacular new studies of a huge range of cosmic phenomena ranging from exoplanets to cosmology. We also recommend that Canada participate in

[15] In the prioritizations below, we note NASA's Lynx X-ray Observatory as a possibility for significant Canadian investment. Other opportunities for X-ray astronomy are discussed in Chapter 6, while LRP2020 white papers W024, W031, W034, W036, W041 and W042 provide further details on Canadian ambitions in high-energy and multi-messenger astrophysics.

CFHT, **LSST** and **MSE**; the major new survey capabilities of these three facilities, covering both imaging and spectroscopy, are needed to address a variety of additional pressing science questions set out in Chapter 4.

- **Targeted studies:** In order to be able to study the faintest and most distant objects in the Universe, it is vital that Canada obtain a substantial share of a **very large optical telescope**. Other powerful capabilities for performing detailed studies of individual objects and populations will be provided by **Gemini**, **POEP** and **SPICA**, each of which offers a unique combination of observing modes, instruments and wavelength coverage aimed at filling major gaps in our understanding of the Universe.

At **radio/millimetre/sub-millimetre wavelengths**, facilities fall broadly into the categories of observatories (typically open to competitive proposals from the community, covering many different programs and observing modes of a variety of sizes), and experiments (facilities dedicated to obtaining one main measurement or data set, often centred on cosmology). Canada has had outstanding success at both approaches, in the last ten years most notably through ALMA (an observatory) and CHIME (an experiment). For the coming decade, we recommend that Canada maintain its strong portfolio of both observatories and experiments, and that the Canadian community also pursue hybrid opportunities that exploit the strengths of both approaches:

- **Observatories:** **SKA1** will be a global radio observatory that will position Canadian astronomers to answer a range of fundamental questions about the origins, structure and evolution of the Universe by virtue of its wide field of view and powerful survey capabilities. The **ngVLA** and **ALMA** arrays will be powerful complements to SKA1, focusing on phenomena that can only be understood by observing at higher frequencies (~1-100 gigahertz for ngVLA and ~100-1000 gigahertz for ALMA) and with higher angular resolution. On Canadian soil, **CHORD** will build on the heritage of CHIME and will similarly perform dedicated commensal experiments on cosmology and fast radio bursts, but will operate in a national facility mode that will allow a wide range of users and the development of new science programs.

- **Experiments:** Canada is positioned to maintain its world leadership in studies of the cosmic microwave background through substantial participation in both **CMB-S4** or an equivalent facility on the ground and the **LiteBIRD** mission in space. These two experiments target the cosmic microwave background in distinct ways (deep observations for CMB-S4 and all-sky coverage for LiteBIRD), allowing us to fully exploit this relic radiation for understanding the origins, history and current contents of the Universe.

Virtually all the programs envisaged for these facilities will have intensive needs for theoretical analysis and computational processing, as recommended earlier in this Chapter. Furthermore, while many measurements will rely on the unique capabilities of one particular facility, there are also many questions that can only be answered by the combination of data from two or more different telescopes. Finally, we emphasize the very large breadth of astrophysics research in Canada: in addition to the core facilities prioritized below, Canadian astronomers will continue to have access to and make use of many other current and upcoming telescopes, as described in Chapters 3 and 6, respectively.

We separate our recommendations on observational facilities into distinct categories:

- Large (>$30M) investments in ground-based facilities
- Mid-scale ($5M-$30M) investments in ground-based facilities
- Very large (>$100M) investments in space astronomy
- Large ($30M-$100M) investments in space astronomy
- Additional (<$30M) investments in space astronomy

This division does not reflect any preferences or scientific distinctions. In particular, the ambitious science program that Canadian astronomers envisage will require many different types of astronomy infrastructure. In particular, the astronomy portfolio for the next decade cannot consist solely of the very largest telescopes, but requires substantive investments in facilities across a range of sizes and budgets.

The above categorization also recognizes that the processes for obtaining funding for ground-based and space-based projects are distinct, and that investments at different levels tend to be requested and allocated in different ways. Specifically:

- Large ground-based facilities are typically funded by direct requests to the Government of Canada and then are subsequently managed by the National Research Council (which has a parliamentary mandate to operate and administer any astronomical observatories established or maintained by the Government of Canada);
- Mid-scale ground-based facilities are usually funded by some combination of the Canada Foundation for Innovation (which is the main source of funding for university-led infrastructure projects in Canadian astronomy, along with associated matching funds from provincial agencies and other sources) and the National Research Council;
- Space astronomy missions and associated activities are normally funded by the Canadian Space Agency, with possible additional contributions from the Canada Foundation for Innovation.

Finally, it is important to recognize that there is a wide variation in the time scales for different astronomy projects: a long-term vision for Canadian astronomy must incorporate the fact that some telescopes will not begin taking data until the 2030s, but require imminent Canadian commitments in order to secure future access and leadership.

Modern astronomy projects involve complex interactions with government, industry, local land-owners and international partners, and so it is possible that not every recommendation below will be realized. Recognizing this, we have proposed a diverse and broad portfolio whose science and leadership capabilities will remain robust and compelling should there be any individual shortfalls. Forecasting the various landscapes in which contingency strategies might be needed is outside the scope of this report; CASCA's Long Range Plan Implementation Committee (LRPIC) will have a vital role in recommending alternatives and revised priorities if such situations occur.

Recommended Large (>$30M) Investments in Ground-Based Facilities

Success and leadership for Canadian astronomy require that our community be able to access the world's largest observatories and facilities. We recommend large Canadian investments in four ground-based telescopes. These facilities are all global projects: access will be shared between many countries and consortia, and it is critical that Canadian involvement in these facilities be at a level sufficient to influence scientific and technical decisions. Each of these facilities will excel in multiple science areas highlighted in Chapter 4, and will have a large user base comprising a significant fraction of the Canadian astronomy community.

Our top recommendations are for two well-developed projects that were also the highest priorities in LRP2010, and are now expected to move forward in the next 2-3 years: a **very large optical telescope** (ranked first), and **SKA1** (ranked second). We make additional unranked recommendations for **MSE** and the **ngVLA**: these two projects represent compelling future opportunities for Canada, which should be explicitly ranked once they have been fully developed.

Ranked recommendations for near-term large projects:

> **1. VLOT:** We recommend that Canada participate in a very large optical telescope (VLOT)[16], and that this participation be at a level that provides compelling opportunities for Canadian leadership in science, technology and instrumentation. Canadian access to and participation in a VLOT remains the community's highest ground-based priority; NRC, CASCA and ACURA must ensure that Canada's share in a VLOT remains at the level needed to fulfil the community's ambitions and requirements for scientific discovery, and to maintain a leadership role in facility governance and overall science and technology development. Canada has been a significant partner in the Thirty Meter Telescope (TMT) project since 2003 and has a clear scientific and technical leadership role enabled by funding and support from the federal government and NRC. Noting that the situation is complex and rapidly evolving, at the time of writing Canadian VLOT access is best implemented by continued participation in TMT, either at the currently proposed Maunakea site or at the scientifically acceptable alternative of Observatorio del Roque de los Muchachos. Canadian participation in TMT or in any other VLOT should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed site from Indigenous Peoples and traditional title holders.

[16] A VLOT is an optical/infrared telescope with a mirror of effective diameter ~30 metres.

We recommend that the Canadian community maintain its leadership and expertise in VLOT instrumentation development, which will ensure access to instruments that meet the needs of the community.

We recommend that NRC address any lack of access to a VLOT due to delays in TMT construction through arrangements that give Canadians access to other VLOT facilities.

2. SKA1: We recommend that Canada participate in the construction and operation of Phase 1 of the Square Kilometer Array, in its network of regional centres, and in the project's governance. This will allow Canada to play a world-leading role in a number of transformational projects to be carried out with SKA1. The scientific goals of SKA1 align well with the strengths of Canadian researchers, and scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the past twenty years. Canada's highest priority for radio astronomy should be to fund and participate in SKA1 Design Baseline construction, operations, the accompanying network of regional centres and a staged technology development program at an overall 6% level, commensurate with Canadian scientific ambitions. We emphasize that developing the relevant infrastructure, incorporating the capabilities of a Canadian SKA1 regional centre or equivalent, is necessary for successful Canadian participation in SKA1, and will ensure community access to the processing, storage and user support required to scientifically exploit SKA1. Canada should identify a membership model for Canadian participation in the SKA Intergovernmental Organisation that can provide leadership rights for Canadian researchers and industry, with full scientific access and maximal opportunities for technological tender and procurement. Canadian participation in SKA1 should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of SKA1 sites from Indigenous Peoples and traditional title holders.

Unranked recommendations for future large projects:

- **MSE:** We recommend that Canada play a leading and substantive role in a next-generation widefield spectroscopic survey facility. Meaningful Canadian participation should be at a level of at least 20%, which will also ensure a prominent Canadian role in driving and participating in the VLOT science that will be enabled by such a facility. The best option at present is to pursue the development, design and construction of the Maunakea Spectroscopic Explorer (MSE) at the current CFHT site on Maunakea; this offers a compelling and timely science case with significant history of and potential for Canadian leadership. Should it not prove possible to transition CFHT into MSE, we recommend that Canada play a substantive leadership role in developing the MSE concept at a different site.

  We recommend that the MSE project build on its mature science case and well-developed design, and now undertake essential future steps on the path toward construction. These include obtaining consent from Indigenous Peoples and traditional title holders for the use of any sites needed for the MSE project, and establishing the governance structure and funding model needed to effectively advance this exciting project.

- **ngVLA:** We recommend that Canada pursue technical contributions to and scientific leadership in the proposed Next Generation Very Large Array (ngVLA), pending a positive recommendation on this project from the US Astro2020 Decadal Survey. The capabilities provided by the ngVLA will enable transformational science across many areas of astrophysics. Canada should correspondingly seek engagement with ngVLA that would result in a ~6% share of observing time, comparable with the access sought for SKA1. Canadian participation in ngVLA should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any ngVLA sites from Indigenous Peoples and traditional title holders.

  We recommend that Canada focus its technical contributions to ngVLA on areas that leverage existing or ongoing Canadian work on SKA1 and other facilities. We also encourage exploration of the proposed scientific alliance between SKA1 and ngVLA, which would allow an exchange of observing time between the two facilities.

Recommended Mid-Scale ($5M-$30M) Investments in Ground-Based Facilities

We consider two types of mid-scale investment. First, Canada needs to continue reaping the benefit of **current facilities** in which we have made large previous investments. Continuing commitment is needed to retain access to these facilities, to upgrade these telescopes with new instruments and technologies, and to sustain our international competitiveness. Below we recommend that Canada continue to invest in **ALMA**, **Gemini** and **CFHT.**

Second, Canada should make new mid-scale investments in **future facilities**, both by constructing our own mid-scale telescopes, and by participating in new large international projects. The former provide targeted opportunities for novel science and serve as pathfinders for future large programs, while the latter allow us to make key focused contributions to some of the world's most powerful new observatories. Below we recommend that Canada construct the **CHORD** facility as a next-generation "made in Canada" successor to CHIME, and that we contribute to and participate in the upcoming **CMB-S4** (or comparable facility) and **LSST** projects.

We recommend the following current and future facilities, separately ranked by priority in each category. All six projects substantially advance Canadian astronomy's needs and opportunities.

Recommendations for continued mid-scale investments in current facilities:

1. ALMA: We recommend that Canada continue to fund the Atacama Large Millimeter/submillimeter Array (ALMA) at the amount needed to maintain our current level of access, that the Canadian community identify components of future ALMA development in which we can play a role, that Canadians continue to seek leadership of ALMA large programs, and that we keep Canadians fully trained and engaged in ALMA as new capabilities become available. ALMA is an unquestioned success story, and has become a world-leading scientific facility that has had significant Canadian uptake, benefit, and output. ALMA remains the key facility for answering many frontier scientific questions. In the 2030s and beyond, there will be many exciting options for ALMA upgrades and expansions, which are likely to be considerations for future mid-term reviews and long-range plans. Canadian participation in ALMA should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

2. Gemini: We recommend that Canada remain an active participant in the Gemini Observatory over the next decade. Gemini continues to be a foundational component of Canadian observational capabilities, plays a key role in training and instrumentation development, and enables research across an incredibly wide range of science topics. Substantial recent investments and new instrumentation make it an exciting time for Canada to be a Gemini partner, and should lead to increased productivity, impact and oversubscription rates. The Gemini Observatory will be a key part of Canada's observational capabilities in the era of 30-metre telescopes. Gemini will be an important testbed for future instrumentation and will offer capabilities not offered by 30 metre-class telescopes until well into the 2030s.

We encourage broad community consultation leading up to the next Gemini assessment point in 2024 on what specific share of Gemini is appropriate for Canada in the next Gemini International Agreement, and on how the negotiation of the Maunakea master lease will affect the status of Gemini North. Canadian participation in Gemini should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

3. CFHT: We recommend continued Canadian participation in the Canada-France-Hawaii Telescope (CFHT) at least until the ongoing Large Programs are complete. During this period, Canada should work with the other CFHT partners to maximize unique high-impact science while reducing costs, for example by reducing the instrument complement or by further prioritizing Large Programs. Once the ongoing Large Programs are complete, Canadian involvement in CFHT will depend on whether CFHT transitions into MSE. Should MSE go ahead at the CFHT site, we recommend that Canada, its CFHT partners, and other relevant stakeholders plan for a future that involves moving SPIRou to another telescope, as this new instrument has the capability to provide high-impact science for at least a decade. Should CFHT not transition into MSE, we recommend that the Canadian astronomy community decide what approach will provide optimal access to northern wide-field capabilities in the optical, ultraviolet and near-infrared, which may mean leaving the CFHT partnership in order to pursue other opportunities (participation in Subaru is one possibility; see the section on Subaru in Chapter 6). Canadian participation in CFHT should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

Recommendations for new mid-scale investments in future facilities:

1. CHORD: We recommend funding and implementation of the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD). CHORD is a unique facility that leverages existing Canadian world scientific leadership, designed from the outset as a national facility. The expansion of capabilities and community access from CHIME will enable exciting and timely science on fast radio bursts, line intensity mapping, pulsars, and many other science areas. The very large data flows anticipated from CHORD will require an expansion of Canada's digital research infrastructure capabilities in radio astronomy, and will help the community prepare for the data challenges of SKA1. Construction and operation of CHORD should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.

2. CMB-S4: We recommend participation in the Cosmic Microwave Background Stage 4 (CMB-S4) experiment, or other comparable facility. Involvement now will let us take leadership roles in defining the overall project. Canadians are world-leaders in all areas of cosmic microwave background research, including detector readout systems, systems integration, pipeline, mapmaking, theory, and interpretation. For continued leadership in this field, it is essential that Canada be involved in CMB-S4 or another comparable facility. Such participation is also highly complementary to LiteBIRD, which we recommend as a space-based priority below. Canadian participation in CMB-S4 or a comparable facility should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders.

3. LSST: We recommend that Canada pursue a route for national membership in the Legacy Survey of Space and Time (LSST). The science enabled by the LSST dataset is unprecedented and will provide foundational data for projects on facilities such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1. At this time, LSST and its funding agencies are still in the process of defining the parameters and requirements for a Canadian partnership in this project. Successful and meaningful Canadian participation in LSST will require development of the relevant digital infrastructure, which will also contribute significantly to the overall international success of the facility. Canadian participation in LSST should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime.

Because some mid-scale projects are conceived and executed on relatively short time scales, the future facilities that appear above cannot constitute a comprehensive list of all the opportunities that may arise over the next decade. We anticipate that there will be newly emerging mid-scale investment opportunities to consider at the time of the next mid-term review in 2025.

Recommended Very Large (>$100M) Investments in Space Astronomy

Canada has a rich heritage of success in space-based astronomy. Participation in multiple new space astronomy missions is needed to maintain our expertise and skill base, and to address the broad scientific needs of the Canadian astronomy community. Most notably, there are specific opportunities for significant Canadian leadership in space astronomy in the coming decade, as well as opportunities to lay the foundations for participation and leadership in missions to be launched in the 2030s and beyond. To capitalize on all these prospects, Canada should seek to be a leader or significant partner in one major space astronomy mission over the next decade. We assert that Canada can lead one very large space astronomy mission with a budget greater than $100M each decade, recognizing that this would require additional funding beyond the CSA A-base budget and thus a separate request to the Government of Canada to the Government of Canada. In order to successfully compete for funding against other possible expenditures of the CSA's finite budget, investments at this scale will need to offer outstanding prospects for Canadian science, HQP training, and technical/industry leadership. Canada's priorities for space astronomy will be incorporated into CSA's forthcoming "Space Science Vision 2020" document, which will put these missions within the context of CSA's other programs.

Our highest recommendation at the very large investment scale is for **CASTOR**, an exciting mission with a broad and compelling science case, and which would be Canada's first marquee space astronomy mission. Our second ranking in this category is for significant Canadian participation in a **NASA flagship mission** (HabEx, LUVOIR, Lynx, or Origins).

1. **CASTOR:** We recommend that the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) be approved for development toward launch. The CASTOR mission is a mature concept that has a world-leading and transformational science case, strong and long-standing community support, substantial interest and involvement from Canadian industry, and enthusiastic international partners who are looking to Canadian leadership to develop and fly a wide-field optical-ultraviolet space telescope. CASTOR will also provide a superb complement to JWST and other forthcoming optical and infrared facilities. A top priority in LRP2010 and MTR2015, CASTOR continues to be an outstanding prospect for Canada's first marquee space astronomy mission. It will be vital to engage with the federal government to fund this very large mission, and to work closely with international partners like JPL/NASA and IIA/ISRO.

2. **Hardware, Scientific and Technical Contributions to NASA Flagships:** We recommend that Canada contribute ~$100M in hardware to a flagship astrophysics mission selected by NASA, and also contribute scientifically and technically to such a mission as recommended under Additional Investments below. However, such a

hardware contribution should be regarded overall as a lower priority than investing in CASTOR, LiteBIRD and SPICA at the recommended levels. A significant hardware contribution to a NASA flagship astrophysics mission would strengthen Canada's standing as a strong international partner in space astronomy. Ahead of the 2025 midterm review, Canadian astronomers should work with the CSA and industrial partners to identify potential hardware contributions to the selected NASA flagship(s) and, where appropriate, the CSA should support technology development studies. CASCA's LRP midterm review in 2025 would then be in a good position to provide guidance on an eventual contribution to a flagship mission.

Recommended Large ($25M-$100M) Investments in Space Astronomy

We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support missions and mission contributions up to $100M.

Our highest recommendation at the large investment scale is for **LiteBIRD**, a JAXA-led mission to study the cosmic microwave background. Our second ranking is for **SPICA**, an ESA-led mission featuring a highly-sensitive cooled mid-infrared telescope. Both LiteBIRD and SPICA offer a strong portfolio of ancillary science activities, provide a pathway to major Canadian technical and scientific leadership, and will result in excellent opportunities for HQP training and engagement with industry. The expected return on investment is high in both guaranteed observing time and industry opportunities.

1. **LiteBIRD:** We recommend Canadian participation in the Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD). This participation should correspond to the complete life cycle of LiteBIRD, including hardware, mission operations, and science analysis. By focusing on the polarization of the cosmic microwave background at large angular scales, LiteBIRD will be an excellent complement to the ground-based CMB-S4 facility, and will provide an outstanding opportunity for Canadian cosmologists to make unique discoveries.

2. **SPICA:** We recommend Canadian participation in the Space Infrared Telescope for Cosmology and Astrophysics (SPICA). This will require both a commitment of funding for the currently identified Canadian contribution to SPICA, and confirmation from CSA of Canadian interest in SPICA participation in the context of the pending (April 2021) ESA downselect. The SPICA mission will leverage substantial Canadian heritage and leadership in infrared space astronomy, and can revolutionize our understanding of cold gas and dust throughout the Universe by providing unique access to far-infrared wavelengths.

Recommended Additional (<$25M) Investments in Space Astronomy

To allow Canadian space astronomy to focus on a marquee mission and one or two other large programs, participation in other missions by the traditional route of small hardware or other contributions (up to $25M) should be limited. Mission participation should be competitively selected and should fulfill the criteria of offering outstanding prospects for Canadian science, HQP training, and technical/industry leadership.

We recommend that the Canadian government provide CSA with A-base funding for space astronomy at the level of at least $15M per year to support the preparatory activities (through phase A) for missions and mission contributions of all sizes, and scientific activities for missions to which Canadian astronomers contribute, regardless of whether the CSA has made a formal contribution.

In the immediate future, the CSA's highest priority in space astronomy should be **JWST**. As longer-term priorities, we recommend that CSA approve the development of **POEP** and seek opportunities for scientific and technical participation in the next **NASA flagship mission** (HabEx, LUVOIR, Lynx, or Origins).

1. **JWST:** We recommend that the CSA maintain financial support to the James Webb Space Telescope (JWST) mission and associated Canadian science for the entirety of the observatory's lifetime. Canada has already made a very large investment in this project, and continued support will leverage this investment for the highest possible science yield.

2. **POEP:** We recommend development of the Photometric Observations of Extrasolar Planets (POEP) mission. The goal should be to enable a launch in the 2025 timeframe, to allow follow-up of exoplanet discoveries made with TESS and CHEOPS, and to provide significant overlap with complementary future space astronomy missions such as JWST, ARIEL, PLATO and CASTOR. POEP has the potential to provide high science impact on exoplanets and the outer solar system for a relatively small investment, and will allow Canada to maintain leadership in small-satellite astronomy.

3. **Scientific and Technical Participation in NASA Flagships:** We recommend that the CSA provide funding that enables Canadian scientific and technical participation in preparatory activities for the NASA flagship mission(s), through design reference missions, analysis software, instrument design, science teams, working groups, etc. Any such opportunities should be disseminated widely, and appointments made by CSA should take place through an open and competitive process. These scientific and technical contributions should be pursued as soon as circumstances allow.

Chapter 6: Future Landscape

In this Chapter, we review the resources considered by LRP2020 for the next decade of theoretical astrophysics, digital research infrastructure, ground-based facilities, and space astronomy missions. Some of these were indicated in Chapter 5 as key priorities for Canadian astronomy over the next decade; we here provide further details on these topics, and repeat the recommendations from Chapter 5. We also summarize and comment on other facilities and programs that have been considered by the LRP2020 panel. The community input upon which these summaries and recommendations have been based can be found in the corresponding white papers and reports. Additional recommendations on funding, governance, personnel, and the role of astronomy in Canadian society are provided in Chapter 7.

Theoretical Astrophysics

Not included in the September release.

Digital Research Infrastructure

Not included in the September release.

Ground-based Facilities: Optical and Infrared

Optical telescopes are among the earliest astronomical instruments. The history of large ground-based telescopes in Canada dates back more than a century. Modern ground-based optical and infrared (OIR) telescopes cover the wavelength range 0.3-10 micrometres; the specialized capabilities of individual facilities allow for discovery across different domains (such as time-variability or high-resolution imaging). In this section we review all optical and infrared facilities that have been considered for LRP2020, and provide specific recommendations for those programs considered as key priorities for the next decade of discovery. Facilities are listed in alphabetical order, with recommendations from Chapter 5 repeated where appropriate.

Table 2: Costs and schedules of recommended ground-based optical and infrared facilities (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Project	Anticipated Cost to Canada		Canadian share of observing time[17]	Construction start	Ops start
	New Construction Costs	Operations			
CFHT	N/A	US$4.0M/year (Canadian contribution in calendar year 2020)	42.5%	1974	1979
Gemini	N/A	US$6.0M/year (Canadian contribution in calendar year 2020)	18.15%	1994	1999-2000
LSST	N/A	$3M[18]/year in 2020-dollars (in-kind)	Full access to survey data	2015	2023
MSE	$110M in 2018-dollars	$7M/year in 2018-dollars	20%	2026	2031
VLOT (TMT)[19]	TBD[20]	US$7M[21]/year in 2020-dollars	15%	TBD	2033 or later

[17] For facilities that are not yet operational, the share listed is provisional or proposed. Note that the share of Canadian observing time is not necessarily derived from or related to the Canadian share of construction or operations costs.
[18] LSST is not accepting cash funds from its partners to cover operations. The amount listed is the cost of in-kind Canadian contributions to LSST operations.
[19] At the time of writing Canadian access to a very large optical telescope is best implemented by continued participation in TMT, sited either at Maunakea, Hawai'i or Observatorio del Roque de los Muchachos in the Canary Islands.
[20] In 2015, the Canadian government committed $243.5M for specific TMT activities, including NFIRAOS and enclosure construction. Any additional construction costs are not yet determined.
[21] The annual operations cost for TMT constructed on Maunakea vs TMT constructed on Observatorio del Roque de los Muchachos are similar to within a few percent.

Arctic Astronomy

Antarctica is known to offer superb conditions for optical and infrared astronomy, including long unbroken periods of darkness, cold and dry conditions that minimize atmospheric contamination, excellent image quality, and a sky mostly free of the trails from satellite constellations. Similar conditions may be obtainable in the high arctic regions of Inuit Nunangat, with the added advantages that such sites are easier to reach than Antarctica and are accessible year round. In the past 10-15 years, Canadian astronomers have conducted site testing at the Polar Environment Atmospheric Research Laboratory (PEARL) (latitude 80º N) on Ellesmere Island in Nunavut, with comparison to three remote high coastal mountains elsewhere on Ellesmere. These campaigns have shown the potential for superb image quality, comparable to Maunakea in Hawai'i and Cerro Tololo in Chile and far better than anywhere else in Canada. Should these imaging prospects be realized, even a small to moderate size telescope at such a site could be a world-class observatory and could make significant research contributions. However, the existing site studies are still only preliminary: a conclusive study will require data taken over multiple winters, employing a tower away from the deleterious effects of the PEARL facility.

The LRP2010 report recommended: (1) that image quality in the High Arctic be fully characterized at multiple sites; (2) that confirmation of a high-quality site should be followed by design, science and technical studies for a 1-4 metre telescope; and (3) that if such studies demonstrated a strong and feasible case, construction of such a telescope should proceed. A distributed network of small telescopes has since been proposed for the PEARL site, with a collective aperture of about a metre. However, this has not advanced beyond a concept study, and there has been no site-testing or other data taking at PEARL since 2013, owing to a lack of funding and the challenging logistics.

Optical and infrared astronomy from the Arctic remains an exciting future option for Canada, but the site conditions, feasibility and cost are yet to be established. Consent from Indigenous Peoples and traditional title holders for astronomical activity at any proposed site, backing from the Canadian astronomy community and associated funding will all be needed before this possibility can be advanced further. Potential funds might be on offer from the Department of National Defence for orbital debris studies, and also from government agencies interested in attracting international investment..

We separately note Arctic radio astronomy as a new focus of activity. Canadians have been testing the low-frequency radio environment at McGill Arctic Research Station (latitude 79°N) for global reionization experiments, with pathfinder elements deployed in 2018. There are also plans to use the new 12-metre Greenland Telescope to image supermassive black holes as part of the Event Horizon Telescope.

CFHT

The Canada-France-Hawaii Telescope (CFHT) is a 3.6-metre optical/infrared telescope on the summit of Maunakea. CFHT has been operating since 1979 and has made broad contributions across astronomy and cosmology, enabled by the combination of innovative instrumentation and the best image quality on the mountain. Leadership in CFHT allowed Canadians to conduct the first legacy surveys on a 4m-class telescope, which had lasting impact in the astronomy community by providing some of the most accurate supernova cosmology results and the first galaxy cluster redshift surveys.

CFHT is a partnership between the National Research Council (NRC) of Canada, the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawai'i (UH). Canada has a 42.5% share of CFHT, and currently makes an annual cash contribution of US$3.3M (2020) to operations. Canadian astronomers can obtain CFHT observing time through the Canadian Time Allocation Committee (CanTAC), or through calls for CFHT Large Programs. For time awarded by CanTAC, around 60-70 observing proposals are currently submitted per year, with an oversubscription ratio of 2-4. Four CFHT Large Programs are currently being executed, all of which have substantial Canadian leadership and involvement. The Canada-France Imaging Survey (CFIS) Large Program is part of the larger UNIONS project that has enabled Canadian participation in the Euclid mission led by the European Space Agency (ESA). There have been more than 800 Canadian-led CFHT publications, which have been cited more than 40,000 times; the highest impact papers have been ground-breaking discoveries on topics such as globular clusters, galaxy evolution, and dark energy. Canadians are leading the proposed redevelopment of CFHT and its site as the Maunakea Spectroscopic Explorer (MSE; see below).[22]

The current instrumentation suite for CFHT consists of two imagers (MegaCam and WIRCam), two spectrographs (ESPaDOnS and SPIRou) and an imaging Fourier transform spectrometer (SITELLE). MegaCam, WIRCam and ESPaDOnS are around 15 years old. MegaCam still provides the only wide-field near-ultraviolet imaging capability on a 4-metre or larger telescope, a key capability for cosmological measurements that complements the data sets from Euclid, the Roman Space Telescope (formerly WFIRST), and the Vera C. Rubin Observatory (formerly LSST). SITELLE and SPIRou have begun taking data just in the last few years and are uniquely powerful in their science areas. With one of the largest fields of view of any integral field spectrograph, SITELLE offers unprecedented capability for mapping the physical conditions in nearby galaxies and star-forming regions. SPIRou's high-precision radial velocity measurements provide the ability to search for exoplanets around low-mass stars and

[22] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

investigate the physical processes at play during the first million years of star-and-planet systems.

Recommendation: We recommend continued Canadian participation in CFHT at least until the ongoing Large Programs are complete. During this period, Canada should work with the other CFHT partners to maximize unique high-impact science while reducing costs, for example by reducing the instrument complement or by further prioritizing Large Programs. Once the ongoing Large Programs are complete, Canadian involvement in CFHT will depend on whether CFHT transitions into MSE. Should MSE go ahead at the CFHT site, we recommend that Canada, its CFHT partners, and other relevant stakeholders plan for a future that involves moving SPIRou to another telescope, as this new instrument has the capability to provide high-impact science for at least a decade. Should CFHT not transition into MSE, we recommend that the Canadian astronomy community decide what approach will provide optimal access to northern wide-field capabilities in the optical, ultraviolet and near-infrared, which may mean leaving the CFHT partnership in order to pursue other opportunities (participation in Subaru is one possibility; see the section on Subaru below). Canadian participation in CFHT should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 5).

Gemini

The Gemini Observatory has been a fundamental optical/IR facility for Canada for over two decades, offering a large suite of instruments on two 8-metre telescopes: a northern facility on Maunakea in Hawai'i and a southern facility on Cerro Pachón in Chile. Gemini is currently funded by a partnership of six countries: the United States, Canada, Chile, Brazil, Argentina and Korea. Canada's share in the partnership is currently 18.15%. Canada has recently extended the agreement to partner in Gemini through 2027, with an assessment point for the next Gemini International Agreement planned for 2024.

Gemini has a strong history of scientific discovery, including the Canadian-led first image of a multi-planet system beyond the solar system, studies of high-redshift quasars, and constraints on dark energy from supernovae. Over the next five years Gemini will enjoy a renaissance, with the commissioning of a revitalized instrumentation suite that is very well-aligned with the general needs of the Canadian astronomical community into the 2020s and beyond. As examples, the capabilities of these new instruments will enable studies of the chemical make-up of the Milky Way halo, early evolution of stars and planetary systems, the contents of nearby and distant galaxies, and the rapid follow-up of newly-discovered variable and transient objects. A new Gemini-North adaptive optics system represents a significant investment from the US National Science Foundation, while the Canadian-led Gemini Infrared Multi-Object Spectrograph (GIRMOS) will revolutionize our ability to study the faintest, oldest and most distant objects in the Universe and to probe the formation of stellar and planetary systems.

Over the past decade, Gemini has introduced two new programs to increase its impact. The first is a Fast Turnaround program which offers roughly 10% of the telescope time to a monthly proposal submission and assessment, with data obtained 1-4 months after submission. The Canadian Gemini Office originally led the effort to develop the necessary software to support this program and Canadian PIs have been awarded nearly 40% of the time allocated through it. Secondly, as of 2014, Large and Long Programs (LLPs) are now allocated up to 20% of the observing time, allowing for proposals of projects that require significant time, potentially over several semesters. Although to date only a small number of Canadian PIs have been awarded time for LLPs, their programs are among the largest ever accepted on Gemini, and exceed the share of time allocated by Canada for LLP participation. Canadians are also active participants in many US-led LLPs.

Canadian oversubscription rates for Gemini have declined over the past several years, but still exceed 2:1; some instruments and modes are even more heavily oversubscribed. Canadian astronomers are productive users of both telescopes. Canadian Gemini papers (those with a Canadian author or co-author) have a higher impact than that of the average Gemini paper. Canadian papers based on Gemini-South data have been more impactful compared to those from Gemini-North, primarily due to the very strong impact of the Gemini Planet Imager on Gemini South. Canada's share of Gemini has facilitated many student-led programs, and Gemini has thus proven to be a powerful thesis-producing machine for Canada. There are now 63 MSc and PhD theses utilizing Gemini data, with more in progress. Currently, an average of five Canadian theses are produced per year using Gemini data.

The Gemini Observatory will continue to provide access to both hemispheres of the sky,[23] performing pathfinder science that will enable programs on 30 metre-class telescopes and providing capabilities that those telescopes will not offer for some time (such as high-resolution spectroscopy in the northern hemisphere). It will also play a key scientific role in follow-up and characterization of phenomena discovered with LSST, ALMA, JWST, MSE and SKA1.

Recommendation: We recommend that Canada remain an active participant in the Gemini Observatory over the next decade. Gemini continues to be a foundational component of Canadian observational capabilities, plays a key role in training and instrumentation

[23] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

development, and enables research across an incredibly wide range of science topics. Substantial recent investments and new instrumentation make it an exciting time for Canada to be a Gemini partner, and should lead to increased productivity, impact and oversubscription rates. The Gemini Observatory will be a key part of Canada's observational capabilities in the era of 30-metre telescopes. Gemini will be an important testbed for future instrumentation and will offer capabilities not offered by 30 metre-class telescopes until well into the 2030s.

We encourage broad community consultation leading up to the next Gemini assessment point in 2024 on what specific share of Gemini is appropriate for Canada in the next Gemini International Agreement, and on how the negotiation of the Maunakea master lease will affect the status of Gemini North. Canadian participation in Gemini should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 5).

LSST

The Legacy Survey of Space and Time (LSST) is slated to begin operations in 2022 using the 8.4-metre optical telescope[24] of the Vera C. Rubin Observatory, now under construction on Cerro Pachón in Chile. The Vera C. Rubin Observatory was the highest recommended ground-based facility in the US Astro2010 decadal review of astronomy, and is the first telescope in its class designed to study the optical transient universe. The LSST will be a 10-year survey of the sky that will deliver a 500-petabyte set of images and data products, which will address some of the most pressing questions about the structure and evolution of the universe, its evolution and the nature of many discrete objects. The impact of LSST will be felt in all fields of astronomy.

The survey is designed to address four key science areas: dark matter and dark energy, hazardous asteroids and the remote solar system, the transient optical sky, and the formation and structure of the Milky Way. The scientific questions that LSST will address are profound, and yet the concept behind the design of the LSST program is remarkably simple: to conduct a deep survey over an enormous area of sky at a cadence that provides images of every part of the visible sky every few nights, and to continue in this mode for ten years to

[24]The telescope itself was formerly known as the Large Synoptic Survey Telescope (LSST); the recast acronym now refers to the survey to be undertaken with this telescope.

achieve astronomical catalogs thousands of times larger than have ever previously been compiled.

LSST will be a powerful new survey that will enable transformative science in the studies of transient objects and wide-field astronomy. The high data volume stream originating from this program will require specialized management in order to capitalize on the information within the data. A limited set of LSST data products will be made public world-wide. However, much of the data release will be delayed, and/or in a form impractical to access for individual astronomers without access to a platform designed to extract meaningful products of specific design from the continuous stream of data. The creation of data management platforms generating tailored data products is therefore critical to realizing LSST's scientific potential. The strongest science benefit will come from the synergy of LSST with other Canadian facilities that will follow-up the transient alerts and discoveries flagged in the survey data. Much of the key physics will come from data projects launched on other facilities, such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1, initially motivated by LSST data.

In 2016, the University of Toronto signed a memorandum of agreement with the LSST Corporation on behalf of a Canadian LSST consortium, and Canada has been correspondingly recognized by LSST as a potential international contributor. Proposed Canadian contributions include the infrastructure and personnel (which are the subject of a pending $15M CFI proposal) to develop a science platform, and an archive at the Canadian Astronomy Data Centre (CADC) to host enhanced public LSST data products. The intent is that these efforts will be formally recognized by LSST and its funding agencies as substantive in-kind contributions to the project, facilitating access to proprietary LSST data for all Canadian astronomers. The total cost of these contributions --- the CFI proposal amortized over 10 years, combined with the cost of data processing, storage for alerts and a publicly available data archive --- will be approximately $3M per year over the next decade.

Recommendation: We recommend that Canada pursue a route for national membership in LSST. The science enabled by the LSST dataset is unprecedented and will provide foundational data for projects on facilities such as Gemini, MSE, a VLOT, ALMA, ngVLA and SKA1. At this time, LSST and its funding agencies are still in the process of defining the parameters and requirements for a Canadian partnership in this project. Successful and meaningful Canadian participation in LSST will require development of the relevant digital infrastructure, which will also contribute significantly to the overall international success of the facility. Canadian participation in LSST should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project's lifetime (see recommendation in Chapter 5).

MSE

The Maunakea Spectroscopic Explorer (MSE) began as a Canadian-led concept for a next-generation Canada-France-Hawaii Telescope (ngCFHT) during LRP2010. MSE is a project to design and construct a wide-field spectroscopic telescope at a site with excellent natural seeing, and in so doing to continue the tradition of Canadian leadership in wide-field astronomy established with CFHT. MSE is an end-to-end science platform for the design, execution and scientific exploitation of transformative, high-precision spectroscopic surveys at low-, medium-, and high-resolution from 0.37 to 1.8 micrometres. MSE will unveil the composition and dynamics of the faint Universe, and will impact nearly every field of astrophysics across spatial scales from individual stars to the largest-scale structures in the Universe. Canadian astronomers were very active in the leadership that developed the strong and diverse MSE science program, which includes the following pillars: high-resolution stellar spectroscopy to understand the chemistry and motions of distant Milky Way stars, studies of galaxy formation and evolution over billions of years, a large-volume redshift survey to constrain cosmological parameters, measurements of the dark matter halos of Milky Way satellites, and the calibration of black hole mass estimates for millions of quasars.

The MSE design features an 11.25-metre aperture telescope dedicated to multi-object spectroscopy with 4300 fibres over a 1.5-degree^2 field of view. MSE is proposed to be located at the current CFHT site on Maunakea,[25] replacing the dome with a new enclosure 10% larger than the current size, while leaving the foundation and much of the remaining infrastructure intact. It is expected that 80% of useful observing time will be dedicated to large, multi-year Legacy Surveys proposed by MSE partners and chosen in a competitive, peer-reviewed process. The remaining 20% of observing time will be allocated to the partners, based on their relative share in MSE, for smaller strategic surveys. A set of Design Reference Surveys will be created and iterated during the design and construction phases, so that the MSE science community will be ready to take full advantage of all of MSE's capabilities.

MSE has the potential to be a critical hub in the emerging international network of front-line astronomical facilities over the coming decades, naturally complementing and extending the scientific power of telescopes like SKA1, Euclid, the Vera C. Rubin Observatory, and many other facilities. MSE will have particular synergy with a VLOT, since the overlap in wavelength range and dedication to large surveys means MSE will provide consistent data sets of huge numbers of targets. TMT and other VLOTs will be able to follow up such datasets with higher resolution or deeper observations. Having both MSE and TMT in the Northern hemisphere would maximize the complementarity between the two facilities.

[25] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

The MSE project passed a Conceptual Design Review in 2018, and in November 2018 the CFHT Scientific Advisory Council endorsed MSE as the scientific future of CFHT. The cost to build the MSE conceptual design on the CFHT site is US$420M including risk margins, and the cost to operate the facility is estimated at US$25M/year, all in 2018 dollars. A model with several roughly equal major partners instead of one dominant partner is anticipated, in which Canada would pursue a partnership at the level of 20% ($110M construction, $7M per year operations, 2018 dollars). The current MSE partnership consists of Canada, France, the University of Hawai'i, Texas A&M University, Australia, China, and India, plus observers from the US National Optical-Infrared Astronomy Research Laboratory and a consortium of UK universities and research institutes; developing a governance structure compatible with both government and university decision-making processes will be important for the project's future. The MSE Science Team consists of approximately 400 scientists worldwide, including approximately 40 from Canada and an equal number from France, exceeded only by the number of members from the USA.

Recommendation: We recommend that Canada play a leading and substantive role in a next-generation widefield spectroscopic survey facility. Meaningful Canadian participation should be at a level of at least 20%, which will also ensure a prominent Canadian role in driving and participating in the VLOT science that will be enabled by such a facility. The best option at present is to pursue the development, design and construction of the Maunakea Spectroscopic Explorer (MSE) at the current CFHT site on Maunakea; this offers a compelling and timely science case with significant history of and potential for Canadian leadership. Should it not prove possible to transition CFHT into MSE, we recommend that Canada play a substantive leadership role in developing the MSE concept at a different site.

We recommend that the MSE project build on its mature science case and well-developed design, and now undertake essential future steps on the path toward construction. These include obtaining consent from Indigenous Peoples and traditional title holders for the use of any sites needed for the MSE project (see recommendation in Chapter 5), and establishing the governance structure and funding model needed to effectively advance this exciting project.

SDSS-V

The Sloan Digital Sky Survey (SDSS) is one of the most ambitious and influential surveys in the history of astronomy, and has resulted in hundreds of publications by Canadian astronomers. SDSS consists of a series of very wide field optical surveys of the sky, including both photometry and spectroscopy. The original SDSS project, which commenced in 2000, provided a public release of uniform, well-calibrated optical photometry and spectroscopy over large parts of the sky, and it has been heavily used for scientific studies ranging from asteroids to the large-scale structure of the Universe. SDSS-II, SDSS-III and SDSS-IV followed, providing fundamental insights into exoplanets, Galactic structure, galaxy evolution, large-scale structure and cosmology.

SDSS-V is now in the final planning stages, with observations to commence in late 2020. SDSS-V will be a panoptic spectroscopic survey that will continue the SDSS tradition of innovative data and collaboration infrastructure, with a focus on mapping of our Galaxy, supermassive black holes, and the Local Volume. SDSS-V will be the first facility providing multi-epoch, all-sky, optical and infrared spectroscopy, as well as offering contiguous integral-field spectroscopic coverage of the Milky Way and nearby galaxies.

Institutions can join SDSS-V as full members (costing US$1150k for data access for everyone at that organization), or as associate members (at a cost of US$230k per “slot”, where one slot corresponds to one faculty member or staff scientist, one postdoc, and their students). Contributions can be cash or in-kind. SDSS-V will be governed by an Advisory Council, while collaboration policies will be developed and implemented by a Collaboration Council. Full members will have representation on both these councils, as will associate members (or groups thereof) with at least 3 slots. At the time of writing, three Canadian institutions have committed to associate membership in SDSS-V: University of Toronto (3 slots), University of Victoria (1 slot) and York University (1 slot). With three slots, the University of Toronto has direct representation on the SDSS-V Advisory Council and Collaboration Council, while Victoria and York's single slots do not give them a vote on these councils.

SDSS-V will be a substantial astronomical survey with major and long-lasting impact. While there will be Canadian participants in SDSS-V, there are currently few identified opportunities for significant Canadian leadership, and there is thus not a strong case for membership in SDSS-V to be funded on a national level at the present time. We encourage the SDSS-V community in Canada to identify additional participants and funding, which can provide the foundations for possible discussions regarding a national presence in this project.

Subaru

Subaru is an 8.2-metre optical-infrared telescope run by the National Astronomical Observatory of Japan (NAOJ). It has operated on the summit of Maunakea since 1999, and is the only 10-metre class telescope capable of wide-field imaging. Subaru has a focused, highly successful instrumentation program built upon wide-field imaging (Hyper Suprime-Cam, HSC), wide-field spectroscopy (Prime Focus Spectrograph, PFS) and high-contrast imaging (the Subaru Coronagraphic Extreme Adaptive Optics, SCExAO). There is also ambition at NAOJ to develop a ground-layer adaptive optics system that will serve a suite of wide-field near-infrared instruments.

HSC is an ultra-wide-field camera that has had an enormous impact on our understanding of topics including high redshift galaxies and supermassive black holes, galaxy clusters and low surface brightness galaxies. Currently under construction, PFS is a wide field (1.3-degree diameter) multifibre spectrograph designed for follow-up of HSC's imaging surveys. Among other science goals, the combination of wide-field imaging and spectroscopy of galaxies enables precision measurements of cosmological parameters that will complement space-based surveys (e.g. from Euclid and the Roman Space Telescope). The PFS consortium will have an allocation of several hundred guaranteed nights in return for providing the instrument, and this will be used to conduct one or more large surveys that are now being prepared through the Subaru Strategic Programs (SSP). Attempts by Canadians to obtain funding to join PFS and the associated SSP have not been successful to date.

SCExAO is one of the few dedicated high-contrast imaging spectrographs worldwide. Its main science goals are the imaging discovery and characterization of the thermal near-infrared light of exoplanets and disks around nearby young stars. Some Canadian astronomers have used the Gemini-Subaru time exchange program to access SCExAO, and there is Canadian interest in joining the SCExAO campaign science team for the upcoming exoplanet/disk campaign. The SCExAO team enthusiastically supports Canadian involvement in future instrument developments in science programs and in sharing expertise in data reduction. SCExAO, with its modular approach, would be one of the best instruments to validate Canadian high-contrast technologies for future deployment on 30-metre class telescopes.

Canadians have shown increasing interest in requesting Subaru time through the Gemini-Subaru Exchange Program. NAOJ has been seeking potential partners for Subaru operations, including Canada. Two types of partnership are envisaged: Partners and Associates. Partners (minimum US$2M/yr, for at least three years) require a larger cash contribution than Associates (US$400k/yr for 2 years), can apply for Intensive (5-40 nights) and Large (40+ nights) programs, and have a role in governance. Unlike Partners, Associates do not have a role in governance, and cannot participate in Large Programs.

Subaru will remain the dominant wide field imager in the northern hemisphere for at least a decade[26] and with PFS it will host the only 10-metre class, wide field optical/infrared spectrograph until MSE. Canadian astronomers have correspondingly expressed interest in gaining enhanced access to Subaru's wide field-of-view and set of powerful new instruments. The level of Canadian participation and leadership in Subaru would be at a relatively small level relative to the prospects offered by comparable expenditures on other current and future facilities. We encourage those interested in expanded Subaru access to identify pathways through which Canada could have significant influence on future decisions for the telescope and its large surveys. Increased exploitation of the Gemini-Subaru Exchange Program could be an important component of these efforts.

VLOT

A Very Large Optical Telescope (VLOT) is defined as an optical/infrared facility with a mirror diameter of approximately 30 metres. This is around ten times the collecting area of the world's largest current telescopes, and represents the scale of facility needed to answer frontier questions in observational astronomy, including discovery and characterization of exoplanets, the oldest Milky Way stars and the first galaxies, new tests of general relativity and cosmology, measurements of supermassive black holes in nearby galaxies, and detection and spectral characterization of distant icy bodies in the solar system. Three VLOTs are being planned or constructed: the Thirty Meter Telescope (TMT), the Giant Magellan Telescope (GMT), and ESO's Extremely Large Telescope (ELT).

Canadian access to and participation in a VLOT has for decades been a very high priority for the community (i.e., in both LRP2000 and LRP2010). Based on this support, Canada has been actively involved in the TMT project since the founding of the TMT Observatory Corporation in 2003. India, China, Japan, and several US-based institutions are all also current partners in the project. TMT was poised in LRP2010 to be a major success of the 2010-2020 decade. Indeed, in April 2015, Prime Minister Stephen Harper announced $243.5M to support TMT construction and an envisaged 15% Canadian share of observing time. Canadian astronomers are playing leadership roles in TMT science planning and instrumentation development. Canadian industry is also heavily engaged in the project, particularly through design and construction of the enclosure.

In 2009, the TMT Board of Directors selected Maunakea in Hawai'i as the preferred site for TMT. With GMT and ELT both being built in Chile, TMT is the only VLOT planned for a

[26] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section below) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

northern hemisphere site. The proposal to site TMT on Maunakea had formal support from some groups in Hawai'i, including the Board of Trustees of the Office of Hawaiian Affairs. A Conservation District Use Permit for Maunakea was obtained in 2013, and construction began in 2014 with a groundbreaking and blessing ceremony. However, interventions by Native Hawaiian protectors of the mountain and a 2015 revocation of the TMT construction permit led to a halt on all site work. In October 2018, the Supreme Court of Hawaii upheld the Conservation District Use Permit issued to TMT by the Hawaiian Board of Land and Natural Resources, and a "notice to proceed" with construction was issued in June 2019. Recommencement of construction was planned for July 2019, but demonstrators again intervened. No further construction activity has taken place. A series of discussions between all involved parties and across the Hawaiian community began in July 2019 and is continuing; at the time of writing, there has been no public outcome from these discussions.[27]

The importance of the TMT project to Canadian astronomy is well understood by astronomers, by NRC, and at higher levels of government. In 2016, in response to the reality that siting on Maunakea was not guaranteed, CASCA and ACURA assembled an ad hoc committee[28] to provide an analysis of several proposed alternative sites. This analysis included engagement with the national community of professional astronomers, and was provided to the TMT Board. In October 2016, the Board selected Observatorio del Roque de los Muchachos (ORM) in the Canary Islands as an alternate site for the TMT. The ORM site offers a site of sufficient quality to execute TMT core science, provides relevant existing infrastructure, and maintains TMT's standing as the only VLOT located in the northern hemisphere. The delay from the planned 2014 construction start means that the TMT timeline is now several years behind those of the ELT and GMT, both of which have begun construction. Because of this delay, there is a significant risk that Canadian astronomers will be disadvantaged against astronomers from other countries when foundational discoveries begin coming from the ELT and GMT. It is crucial that Canadians secure at least some initial access to these other facilities as the VLOT era begins.

A VLOT's key technologies and capabilities will enable transformational science. A major Canadian contribution to the TMT project is the NFIRAOS adaptive optics system, the culmination of many decades in pioneering Canadian leadership in this field. NFIRAOS will open up fundamentally new capabilities, increasing sensitivity by a factor of more than 200 over that of current 10-metre class telescopes and enabling unprecedented precision astrometry of both Galactic and extragalactic objects. These capabilities will provide transformative observations of gravitational lensing and microlensing, proper motions of Local Group galaxies,

[27] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around TMT and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

[28] This committee was succeeded by the CASCA-ACURA TMT Advisory Committee (CATAC), which continues to advise both CASCA and ACURA on TMT-related issues and also provided input to LRP2020.

fueling and feedback mechanisms for active galaxies, exoplanets, protoplanetary disks, and much more. Despite the challenges of deep mid-infrared observations from the ground, the high spatial and spectral resolution that can be achieved with a VLOT enables some very exciting exoplanet science that Canadians are eager to tackle. Imaging sub-Saturn mass planets at a separation of 10 astronomical units, detecting biosignatures in transit spectroscopy of Earth-like planets, and measuring the distribution of complex, life-related molecules in protoplanetary disks will all be made possible. There will be a competitive process for designing and constructing successive generations of VLOT instruments. Canada already has ongoing involvement in the development of high-resolution spectrographs on both TMT and ELT, and has ambitions for other instrumentation concepts in future development cycles. The new large-scale integration and test facility at NRC-Herzberg, built for the construction of NFIRAOS, can also be used to enable future Canadian VLOT instrumentation.

While highly-multiplexed spectrographs on 10m-class telescopes will dominate wide-field spectroscopy, large samples of very faint objects require the collecting area of a VLOT. The large aperture of a 30-metre telescope provides the sensitivity needed to explore the stellar populations of faint and low surface brightness galaxies, quasar and galaxy outflows, low-mass satellite dynamics, the initial-final mass relation in stars, low-mass halo stars and white dwarfs, supernovae, and many other topics. TMT in particular is designed as an agile extremely large telescope, well-suited for rapid response, targets of opportunity, and time-variable science. Instruments that can take advantage of this are poised to have a big impact on the largely unexplored field of transient phenomena that vary on timescales of less than a day, in a way that cannot be matched by GMT or ELT. Measurement of radial velocities in objects with very short orbital periods enables, for example, the characterization of high-mass neutron stars, X-ray binaries, exoplanet transits, and close white dwarf binaries (which are the presumed progenitors of some supernova explosions and are potential gravitational wave sources).

Recommendation: We recommend that Canada participate in a VLOT, and that this participation be at a level that provides compelling opportunities for Canadian leadership in science, technology and instrumentation. Canadian access to and participation in a VLOT remains the community’s highest ground-based priority; NRC, CASCA and ACURA must ensure that Canada’s share in a VLOT remains at the level needed to fulfil the community’s ambitions and requirements for scientific discovery, and to maintain a leadership role in facility governance and overall science and technology development. Canada has been a significant partner in TMT since 2003 and has a clear scientific and technical leadership role enabled by funding and support from the federal government and NRC. Noting that the situation is complex and rapidly evolving, at the time of writing Canadian VLOT access is best implemented by continued participation in TMT, either at the currently proposed Maunakea site or at the scientifically acceptable alternative of Observatorio del Roque de los

Muchachos. Canadian participation in TMT or in any other VLOT should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed site from Indigenous Peoples and traditional title holders (see recommendation in Chapter 5).

Recommendation: We recommend that the Canadian community maintain its leadership and expertise in VLOT instrumentation development, which will ensure access to instruments that meet the needs of the community.

Recommendation: We recommend that NRC address any lack of access to a VLOT due to delays in TMT construction through arrangements that give Canadians access to other VLOT facilities.

Ground-based Facilities: Radio, Millimetre and Sub-millimetre

Canada has decades of leadership in astronomical observations at radio, millimetre and submillimetre frequencies, with highlights ranging from the first ever very long baseline interferometry experiment in 1967, to the 1000+ fast radio bursts that have now been discovered by the CHIME telescope. The future of Canadian astronomy at these frequencies is especially exciting, with opportunities covering both Canadian born-and-bred experiments and large international facilities, and with observational capabilities from 10 megahertz up to 1000 gigahertz. In this section we review the radio, millimetre and submillimetre facilities that have been considered for LRP2020, and provide specific recommendations for those programs considered as key priorities for the next decade of discovery. Facilities are listed in alphabetical order, with recommendations from Chapter 5 repeated where appropriate.

Table 3: Costs and schedules for recommended ground-based radio and sub-millimetre facilities (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Project	Anticipated Cost to Canada		Canadian share of observing time[29]	Construction start	Ops start
	New Construction Costs	Operations			
ALMA	N/A	US$1.8M/year (Canadian contribution in calendar year 2020)	Not fixed[30]	2003	2011
CHORD	$23M	$0.6M/year	100%	2021	2023
CMB-S4 or comparable facility	$4M-$7M	$0.5M/year	Full access to survey data	2021	2026
ngVLA	US$130M in 2018-dollars	US$6M/year in 2018-dollars	6%	2025	2028 (early science)
SKA1	Observatory: $80M in 2017-dollars	Observatory: $8M/year[31] in 2017-dollars	6%	2021	2026 (science verification)
	SKA1 Regional Centre: $45M[32] in 2017-dollars				

[29] For facilities that are not yet operational, the share listed is provisional or proposed. Note that the share of Canadian observing time is not necessarily derived from or related to the Canadian share of construction or operations costs.
[30] Canadian users of ALMA compete for the 37.5% of ALMA time available to North American researchers, which means Canada has no guaranteed observing time allocation, imposing no minimums and limited by only the quality of the submitted proposals.
[31]Average annual cost for 2021-2030 during the SKA1 construction phase, with costs ramping up towards the end of the decade.
[32] Cost for a Canadian SKA1 Regional Centre over 2021-2030, including processing, storage, networking, and staffing costs.

ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) was the top-ranked priority for a new ground-based facility in the 2000 Long Range Plan. Ten years later, at the time of LRP2010, construction of ALMA's 66 dishes on the Chajnantor plateau in northern Chile was well underway; the first science observations took place in 2011. Since then, ALMA has proven itself to be a high-impact, high-demand observatory, with record numbers of proposals submitted to the past few annual calls and large numbers of highly cited scientific papers across topics from protoplanetary disks to high-redshift galaxies and quasars. Since Cycle 4 in 2016, ALMA has also begun to carry out large programs.

ALMA's scientific impact reaches into nearly every area of astronomy. Highlights include the first image of a supermassive black hole by the Event Horizon Telescope; Canadians led the analysis that extracted the physics, such as black hole mass and spin, from that image. A Canadian-led collaboration has shown that radio galaxies located in clusters and groups can drive molecular gas flows up to tens of kiloparsecs in altitude. Canadians are also leading innovative studies of proto-stellar, proto-planetary and debris disks, including the first systematic study of their morphologies and the location of gaps that can signal unseen planets. The first Canadian-led ALMA large program, Virgo Environment Traced in CO (VERTICO), will map 51 spiral galaxies in the nearby Virgo cluster and use a multi-wavelength approach to quantify the effect of cluster environment on the star-forming molecular gas.

The LRP2010 ALMA white paper laid out eight specific metrics that could be used to judge the success of Canada's participation in ALMA. These metrics ranged from publications to collaborations to student training and leadership in ALMA operations, as well as the successful completion of the Band 3 receivers and ALMA development projects. By these eight metrics, Canada's involvement in ALMA over the past decade has been an unquestioned success. To call out one particular criterion, Canadians are making excellent use of ALMA in training graduate students and postdocs: over half of Canadian first-author papers published through to June 2018 were led by graduate students or postdocs. The first ALMA Large Program led within Canada (VERTICO) is also the first led by a postdoctoral researcher. The successful delivery of these wide-ranging goals argues strongly for Canada's continuing participation in operating and developing ALMA over the next decade and beyond.

The ALMA Observatory has identified a set of short and medium-term development goals that will keep ALMA at the cutting-edge of astronomy and allow it to continue producing transformational scientific results in future decades. The science ambitions of this "Roadmap to 2030" build on the demonstrated achievements of its original science goals. The Roadmap identifies three new science goals with a theme of cosmic origins. "Origins of Galaxies" seeks to trace key elements from the early universe to the peak of cosmic star formation via detection of dust continuum emission and the cooling lines of key atoms (i.e., carbon and oxygen) and molecules, such as carbon monoxide. “Origins of Chemical Complexity” seeks to trace the evolution from simple to complex organic molecules from interstellar gas through star and planet formation to individual solar systems. Finally, “Origins of Planets” sets a goal of resolving the terrestrial planet formation zone in the nearest star-forming regions via dust continuum observations. In addition, ALMA will continue to play a pivotal role in making increasingly more detailed images of supermassive black holes as part of the Event Horizon Telescope.

ALMA’s key science goals for the 2020s in turn motivate new technical developments. Over the next decade, the focus is on expanding the spectral bandwidth of ALMA by a factor of at least two, leading to a corresponding decrease in the integration time required for a variety of scientific programs. This increase in bandwidth requires upgrades to ALMA’s receivers, electronics, and correlator. Improvements to the ALMA Archive are another important focus, particularly in the area of applying data mining to large spectral datasets. There are opportunities for Canadian participation and/or leadership in many of these development areas.

Recommendation: We recommend that Canada continue to fund the Atacama Large Millimeter/submillimeter Array (ALMA) at the amount needed to maintain our current level of access, that the Canadian community identify components of future ALMA development in which we can play a role, that Canadians continue to seek leadership of ALMA large programs, and that we keep Canadians fully trained and engaged in ALMA as new capabilities become available. ALMA is an unquestioned success story, and has become a world-leading scientific facility that has had significant Canadian uptake, benefit, and output. ALMA remains the key facility for answering many frontier scientific questions. In the 2030s and beyond, there will be many exciting options for ALMA upgrades and expansions, which are likely to be considerations for future mid-term reviews and long-range plans. Canadian participation in ALMA should incorporate a set of guiding principles for sites used by astronomy projects, which should acknowledge that ongoing consent from Indigenous Peoples and continuing consultation with all relevant local communities are both essential throughout a project’s lifetime (see recommendation in Chapter 5).

CCAT-prime

The Cerro Chajnantor Atacama Telescope-prime (CCAT-prime) will be a millimetre/submillimetre 6-metre single-dish telescope[33] that will do important science in tracing large-scale galaxy distributions, probing dusty, obscured star formation, and measuring polarized cosmic microwave background foregrounds. Single-dish telescopes like CCAT-prime fill a crucial role in surveying large areas of sky; interesting sources found in such surveys can then be studied in further detail with interferometers like ALMA. CCAT-prime is also an important technological precursor to CMB-S4 and the Simons Observatory.

An international consortium led by Cornell University is building CCAT-prime on Cerro Chajnantor in northern Chile, for completion by 2023 at a total cost of $90M including five years of operations. The very low precipitable water vapour at CCAT-prime's high-altitude site offers an unparalleled mapping speed at its highest observing frequency (860 gigahertz). Canadian astronomers contribute broadly to the CCAT-prime collaboration and propose to build Prime-Cam (PCam), the powerful, first-light camera for CCAT-prime. The wavelength coverage, sensitivity, spatial resolution and large field-of-view of PCam on CCAT-prime will allow it to perform an impressive set of wide-area surveys.

Canadian involvement in CCAT-prime is led by a consortium of universities that have secured funding through institutional and individual grants. The Canadian CCAT-prime team has submitted an $11M proposal to CFI to fund PCam construction. We encourage Canadian participation in CCAT-prime, as a complement to participation in ALMA, CMB-S4, SPICA, and other far-infrared and submillimetre facilities.

CHORD

The Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) is a pan-Canadian project, designed to work with and build on the success of the Canadian Hydrogen Intensity Mapping Experiment (CHIME). CHORD will be an ultra-wideband array of a large number of small-diameter dishes, providing extreme sensitivity over 300-1500 megahertz over a large field-of-view. CHORD will consist of a central array of 512 6-metre dishes sited at the Dominion Radio Astrophysical Observatory (DRAO) near Penticton BC, supported by a pair of distant (1000-3000 km) outrigger stations, each equipped with CHIME-like cylinders and a 64-dish array. With breakthrough sensitivity, bandwidth, and localization capabilities, CHORD will elucidate the nature of fast radio bursts and their precise location within galactic hosts; map

[33] CCAT-prime is a smaller and descoped version of the CCAT concept that was discussed in MTR2015.

the distribution of matter on cosmic scales to reveal the detailed evolution of structure in the Universe; and measure fundamental physics parameters, such as probing neutrino properties and testing General Relativity.

Canadian researchers are leading every aspect of CHORD, and will be developing the critical technologies, analyzing the world-leading data set, and making the crucial discoveries. CHORD will be a national effort that deepens the relationships that have developed in Canada's radio astronomy community through previous CFI-funded collaborations. The core institutions include McGill, the University of Toronto, UBC, the University of Calgary, the Perimeter Institute, and NRC Herzberg, with all Canadian astronomers able to participate in the science teams. CHORD will also enhance the capabilities of the DRAO site and its infrastructure, serving the broad Canadian astronomy community. Internationally, the team will continue their successful partnerships with world-leading groups and forge new links.

The CHORD team is seeking $23M in a pending CFI proposal. The design and costing are based on previous experience with the CHIME and CHIME/FRB projects, both of which were delivered on time and on budget, and are meeting or exceeding performance specifications. Costing for the dishes has been provided by NRC. Seed funding to design and prototype the outrigger stations has been secured from the Gordon and Betty Moore Foundation, part of larger in-kind and cash contributions already pledged or secured. CHORD will have very low operation costs. The outrigger stations and cylinders are under development already, and will be fully commissioned and operating in two years. Once funding is secured, it will take 1-2 years to finalize the design of the dishes for the core and outriggers, and 2-3 years for full construction.

Key technologies required for CHORD have been demonstrated in laboratory settings, and the majority are already operating on-sky in fielded prototype systems. Concerns about handling and processing the deluge of raw data have been largely retired with CHIME's success. For placement of the outriggers, the team is in discussions with existing radio observatories such as Algonquin in Ontario, and Green Bank, Owens Valley and Hat Creek in the USA.

Recommendation: We recommend funding and implementation of CHORD. CHORD is a unique facility that leverages existing Canadian world scientific leadership, designed from the outset as a national facility. The expansion of capabilities and community access from CHIME will enable exciting and timely science on fast radio bursts, line intensity mapping, pulsars, and many other science areas. The very large data flows anticipated from CHORD will require an expansion of Canada's digital research infrastructure capabilities in radio astronomy, and will help the community prepare for the data challenges of SKA1. Construction and operation of CHORD should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 5).

CMB-S4

The Cosmic Microwave Background Stage 4 Experiment (CMB-S4) is envisioned to be the ultimate ground-based cosmic microwave background experiment. Studies of the cosmic microwave background address the questions of how the universe began and the nature of its extreme conditions. The core science case for CMB-S4 includes the search for primordial gravitational waves as predicted from inflation, the imprint on the cosmic microwave background of relic particles including neutrinos, and unique insights into dark energy and tests of gravity on large scales. Facilities at the scale of CMB-S4 are the culmination of a long and strong set of Canadian contributions in this field, recognized by the 2008, 2012 and 2018 Gruber Cosmology Prizes, and by the 2020 Breakthrough Prize for New Horizons in Physics. The CMB-S4 sensitivity to primordial gravitational waves will probe physics at the highest energy scales and cross a major theoretically motivated threshold in constraints on inflation. The CMB-S4 search for new light relic particles will shed light on the early Universe 10,000 times farther back than current experiments can reach.

CMB-S4 is a collaboration between experimental efforts, bringing together previously competitive groups to begin science operations in 2026. Canadian designs for the readout electronics are one of the core proposed technologies. CMB-S4 is largely funded through partnerships between the US National Science Foundation and Department of Energy. For Canada to become a builder participant in CMB-S4 will require significant funding for the development of infrastructure and a dedicated pipeline team. The level of required Canadian contribution to construction is estimated at $4M-$7M, as could be obtained through a future CFI proposal.

As discussed below, there are recent plans for a significant extension to the Simons Observatory called “SO-Enhanced”. The relationship between CMB-S4 and SO-Enhanced is still evolving, and neither project is yet fully funded. It is possible that Canadian cosmic microwave background researchers will need to choose which of these projects to participate in, and it is also possible that only one of these projects will proceed to construction. We focus on CMB-S4, but note that our recommendations apply equally to other cosmic microwave background experiments with comparable science capabilities.

Recommendation: We recommend participation in the Cosmic Microwave Background Stage 4 (CMB-S4) experiment, or other comparable facility. Involvement now will let us take leadership roles in defining the overall project. Canadians are world-leaders in all areas of cosmic microwave background research, including detector readout systems, systems integration, pipeline, mapmaking, theory, and interpretation. For continued leadership in this field, it is essential that Canada be involved in CMB-S4 or another comparable facility. Such participation is also highly complementary to LiteBIRD, which we recommend as a space-based priority below. Canadian participation in CMB-S4 or equivalent should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any proposed sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 5).

JCMT and Future Large Sub-Millimetre Single-Dish Telescopes

The James Clerk Maxwell Telescope (JCMT) is a 15-metre single-dish located at the summit of Maunakea on Hawai'i, and currently observes at 350 and 660 gigahertz. The JCMT has had two core instruments over the past decade, SCUBA-2 and HARP. SCUBA-2 is a revolutionary large-format bolometric camera with substantial Canadian contributions, accompanied by a Canadian Fourier transform spectrometer and polarimeter. HARP is a 4x4 focal-plane array of heterodyne receivers, built by the UK with Canada contributing the correlator.

JCMT has had a broad science impact spanning more than thirty years. Notable Canadian work over the last decade includes leadership of large surveys on deep cosmological fields, nearby galaxies, the Galactic Plane, star-forming molecular clouds in the Gould Belt, debris disks, magnetic fields in star-forming regions, and time-variability of protostellar sources. Canada was a 25% partner in JCMT from first light in 1987 through 2014, when national participation in this facility formally ended as recommended in LRP2010 and preceding reviews. MTR2015 supported efforts to maintain Canadian access to JCMT through various university coalitions, and the Canadian sub-millimetre community successfully obtained such support from 2015 through to 2019. JCMT is currently operated by the East Asian Observatory, while the CADC continues to host the JCMT Science Archive as an in-kind contribution. Canadian astronomers were eligible to lead large JCMT observing program proposals in 2019 and to join accepted new large programs in 2020; there is no guarantee that this access will continue in the future.

A consortium of Canadian universities led by McMaster University have submitted a $2M CFI proposal to contribute toward construction of a new submillimetre continuum camera, which is envisaged to be JCMT's marquee instrument for the next decade.[34] This camera will be able to map star formation and galaxy formation twenty times faster than SCUBA-2. The wide-field mapping capabilities of this new camera will make it a powerful discovery instrument for at least ten years: it will serve as a valuable complement to the high-resolution capabilities of ALMA,

[34] Note that the future of all astronomical facilities on Maunakea is uncertain, both because of the ongoing discussion and consultation around the Thirty Meter Telescope (see VLOT section above) and because the current master lease under which astronomical use of the mountain is managed by the University of Hawai'i ends in 2033.

enhancing the Canadian community's ability to obtain large amounts of ALMA observing time. We encourage continued participation in JCMT through individual funding efforts, including the pending CFI proposal.

There is also significant Canadian interest in more ambitious proposals for large (25+ metre diameter) single-dish submillimetre telescopes such as CCAT-25 and AtLAST. A broad and compelling science program will be one key component of a national path toward participation in such a facility. We support continued development of such concepts, and anticipate discussion of a science and business case for such telescopes in MTR2025.

ngVLA

The Next Generation Very Large Array (ngVLA) is a transformational radio observatory being designed by the US National Radio Astronomy Observatory (NRAO). The ngVLA will consist of a central cluster of 19 (6-metre) dishes in New Mexico, a further 214 larger (18-metre) dishes distributed throughout the US Southwest, plus another 30 (18-metre) dishes spread across North America (including the DRAO site near Penticton, BC), Hawai'i[35] and the Caribbean out to baselines of nearly 9000 km. The ngVLA will provide order-of-magnitude improvements in sensitivity and angular resolution over the current Karl G. Jansky Very Large Array (VLA), and provide continuous frequency coverage from 1.2 to 116 gigahertz.

Observations with the ngVLA will address many aspects of the science questions articulated in Chapter 4. Key science goals for ngVLA include unveiling the formation of solar-system analogues on terrestrial scales, probing the initial conditions for planetary systems and life, charting the assembly, structure, and evolution of galaxies from the first billion years to the present, using Galactic Centre pulsars to make fundamental tests of General Relativity, and understanding the formation and evolution of stellar and supermassive black holes and compact objects in the era of multi-messenger astronomy.

The ngVLA project is awaiting a recommendation from the US Astro2020 decadal survey. The construction cost of ngVLA is estimated at US$2.25B, plus operations costs of US$93M/year. NRAO is seeking international partnerships that will provide 25% of construction and operation costs; the LRP2020 white paper on the ngVLA proposes Canadian participation in the ngVLA at the 7% level. As with other ground-based facilities, radio-frequency interference from satellite constellations (e.g., Starlink) has recently emerged as a possible technical risk to the ngVLA. The effects of this interference are currently unknown, and have not been considered as a basis for the recommendation provided here.

[35]NRAO is considering various ngVLA sites in Hawai'i, but there are no plans to place any ngVLA dishes on Maunakea.

Canadians have been vigorous users of the current VLA. For example, 15% of all VLA papers have had at least one Canadian co-author, with 5% of VLA papers having a Canadian lead. Canadians have been involved in scientific leadership of ngVLA from the very start, are active members on the Executives of the ngVLA's Science Advisory Council and Technical Advisory Council, are leading the organization of science-use case studies and ngVLA-related science meetings, and envisage substantial potential for technical leadership on ngVLA development (e.g., in NRC's composite dish technology also planned for use in CHORD). It is important to note that the science capabilities of ngVLA, SKA1 and ALMA all complement rather than duplicate or compete with each other, and that there is commonality between proposed Canadian technical contributions to ngVLA and SKA1. The ngVLA and SKA1 have evolved with this synergy in mind: the original SKA concept included high-frequency capability similar to that of ngVLA, and the SKA1 and ngVLA projects are investigating a process to establish a scientific alliance. The combination of ngVLA, SKA1 and ALMA can provide Canadians access to next-generation radio observing capabilities over an almost continuous frequency range from 50 megahertz to 950 gigahertz, positioning Canada to be a major player in global radio astronomy in the 2030s and beyond.

Recommendation: We recommend that Canada pursue technical contributions to and scientific leadership in the proposed Next Generation Very Large Array (ngVLA), pending a positive recommendation on this project from the US Astro2020 Decadal Survey. The capabilities provided by the ngVLA will enable transformational science across many areas of astrophysics. Canada should correspondingly seek engagement with ngVLA that would result in a ~6% share of observing time, comparable with the access sought for SKA1. Canadian participation in ngVLA should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of any ngVLA sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 5).

We recommend that Canada focus its technical contributions to ngVLA on areas that leverage existing or ongoing Canadian work on SKA1 and other facilities. We also encourage exploration of the proposed scientific alliance between SKA1 and ngVLA, which would allow an exchange of observing time between the two facilities.

Simons Observatory (SO)

The Simons Observatory (SO) is a cosmic microwave background experiment currently under construction in the Chajnantor Science Preserve in the Atacama Desert in Chile. The originally defined concept, “SO-Nominal”, will be sensitive to both temperature and polarization anisotropies in the cosmic microwave background, and will operate in six bands covering 27 to 280 gigahertz in two separate telescope configurations: three 0.5-metre telescopes to map the sky on large angular scales, and one large-aperture 6-metre telescope for high-resolution science. SO-Nominal will have a total of 60,000 cryogenic bolometers, with first light anticipated for 2023. An upgrade pathway to double the mapping speed by 2025 has also been proposed: this “SO-Enhanced” program adds more dishes and detectors, and adds five years of operations. This would require substantial additional funding, and is awaiting a recommendation by the US Astro2020 decadal survey process.

SO-Nominal is a logical step toward the next-generation cosmic microwave background science goals discussed for CMB-S4 above. An iterative approach has been very successful over the past thirty years of cosmic microwave background research, and the SO collaboration has developed technology and pipelines that are directly applicable to CMB-S4 and LiteBIRD.

SO-Nominal has been funded by a combined US$40M grant from the Simons Foundation, Heising-Simons Foundation and participating US institutions, including Princeton University, the University of California at San Diego, the University of California at Berkeley, the University of Pennsylvania and Lawrence Berkeley National Laboratory. Various Canadian institutions and individuals have been contributing to SO-Nominal through in-kind analysis and computing, but future participation will require cash funding to be applied toward instrumentation and development of the analysis pipeline. We encourage the cosmic microwave background community to pursue the funding required for meaningful participation in SO-Nominal, which is estimated to be at the level of $1M-$2M, and which would give Canadian researchers standing within the SO governance structure. Canadian participation in the more ambitious SO-Enhanced project would require additional funding and would likely require a choice between involvement in SO-Enhanced and CMB-S4, as discussed in our recommendation on CMB-S4 above.

SKA1

The Square Kilometre Array (SKA) is an exciting global observatory that will enable transformational research on the history, contents, extreme conditions, and prospects for life in the Universe. The SKA will be built in two phases, with the first phase (SKA1) representing about 10% of the full facility (SKA2).[36] SKA1 will consist of two sites: an array of ~200 mid-frequency dishes (SKA1-Mid, covering the frequency range 0.35-15.3 gigahertz) in the Karoo region of South Africa, and an array of ~130,000 low-frequency antennas (SKA1-Low, covering 0.05-0.35 gigahertz) in outback Western Australia, with headquarters at Jodrell Bank Observatory in the UK. SKA1 will be the largest and most powerful wide-field radio telescope for the foreseeable future.

The technical specifications, science requirements and anticipated scientific performance of the SKA1 Design Baseline are well established, and almost all elements of that design have passed critical design review (CDR). The System CDR pass in December 2019 confirmed that the Baseline Design is also complete at the system level, and therefore that the project is ready to transition from the design phase to the construction phase; construction is set to commence in 2021.

Scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the last two decades. SKA1 is poised to make fundamental advances across a broad range of fields by virtue of its combination of sensitivity, angular resolution, imaging quality, survey speed and frequency coverage. The scientific goals for SKA1 align well with the strengths of Canadian researchers. Canada is a world leader in studies of pulsars, cosmic magnetism and transients, as well as in low-frequency cosmology. Our multi-wavelength expertise in galaxy evolution, multi-messenger astronomy and planetary system formation – in which radio observations play a critical part – is also a key strength. The Canadian community therefore has the potential to play world-leading roles in a number of the transformational projects to be carried out with SKA1. A proposed 6% participation in the SKA1 Design Baseline is well-matched to Canadian scientific capacity and ambitions. This commitment is estimated to cost $160M in construction and operations contributions over the period 2021-2030.

Canada is a leader in technological development for SKA1 through effective partnerships between universities, NRC Herzberg and industry. Canada's key SKA1 technological capabilities include the design and fabrication of correlators and beamformers, digitizers, low-noise amplifiers, signal processing, and monitor and control. These technologies provide a suite of possible in-kind contributions to offset construction costs, yielding an excellent return on

[36] SKA2 is not yet defined or costed, nor is it related to SKA1 commitments. Once this information exists, future MTRs or LRPs should consider the prospects for Canadian participation in SKA2.

the capital investment required to participate in SKA1 at a level commensurate with our scientific ambitions.

A network of SKA1 Regional Centres (SRCs) will be needed to handle the global science processing, archive and user support needs for SKA1. Canada has the computing platform and archive development expertise to make important contributions to the SRC network that will deliver global SKA1 scientific computing capability. A Canadian SRC would leverage our national compute strength and would provide processing, storage and user support tailored to Canadian SKA1 needs, thereby allowing Canadian astronomers to fully exploit the scientific capabilities of SKA1. The cost of a Canadian SRC (covering both construction and operations) is estimated to be $45M for the period 2021-2030, over and above the construction and operations funding for the telescope itself indicated above; this cost would be part of the total request for SKA1. Because Canada's involvement in SKA1 may be at the intergovernmental treaty level, this computing infrastructure would likely require a separate funding stream from that for general computing resources discussed in the "Digital Research Infrastructure" section above. The infrastructure could be operated by NDRIO, NRC-CADC, universities, or some partnership of these organizations.

Canadian contributions to SKA1 now span twenty years, marked by scientific and technological leadership that persists today within a vibrant metre- and centimetre-wave radio community. Canada at last has the opportunity to reap the scientific benefits of our contributions; an early commitment to construction would maximize our impact on this phase and our technological benefits.

The SKA project is planning to soon become an Intergovernmental Organisation (IGO), governed by a treaty ratified by all participating countries. Canada currently holds Observer status on the Council Preparatory Task Force of the SKA IGO, which is an important step towards participating in SKA1 construction and operations. However, Canada risks forfeiting the opportunity to provide scientific and technical leadership in SKA1 if a path to participation in the IGO is not identified and defined. Lack of IGO participation would also mean we risk missing out on construction tender and procurement, which would significantly worsen the cost-benefit ratio of SKA1 participation.

Recommendation: We recommend that Canada participate in the construction and operation of Phase 1 of the Square Kilometer Array, in its network of regional centres, and in the project's governance. This will allow Canada to play a world-leading role in a number of transformational projects to be carried out with SKA1. The scientific goals of SKA1 align well with the strengths of Canadian researchers, and scientific and technological participation in the SKA has been identified as a top priority for the Canadian astronomical community for the past twenty years. Canada's highest priority for radio astronomy should be to fund and participate in SKA1 Design Baseline construction, operations, the accompanying network of regional centres and a staged technology development program at an overall 6% level, commensurate with Canadian scientific ambitions. We emphasize that developing the relevant infrastructure, incorporating the capabilities of a Canadian SKA1 regional centre or equivalent, is necessary for successful Canadian participation in SKA1, and will ensure community access to the processing, storage and user support required to scientifically exploit SKA1. Canada should identify a membership model for Canadian participation in the SKA Intergovernmental Organisation that can provide leadership rights for Canadian researchers and industry, with full scientific access and maximal opportunities for technological tender and procurement. Canadian participation in SKA1 should be subject to a set of guiding principles for sites used by astronomy projects, centred on consent for the use of SKA1 sites from Indigenous Peoples and traditional title holders (see recommendation in Chapter 5).

Space Astronomy Missions

Observations from space are a key aspect of astronomy because of freedom from atmospheric weather, absorption and distortion, and because some wavelengths are not observable from the ground. Access to and participation in space observatories are an essential element of Canadian astronomy across the entire range of research interests. Canada has played a significant role in past and ongoing space observatories, and has earned a deserved reputation for hardware, data handling, and scientific exploitation. In this Section we discuss the space-based facilities that have been considered for LRP2020. Although Chapter 5 lists the recommended missions in priority order, in this section we comment on all considered missions [37] in alphabetical order,[38] with recommendations from Chapter 5 repeated where appropriate. Additional recommendations to the Canadian Space Agency (CSA) and to the Joint Committee on Space Astronomy (JCSA) are provided in Chapter 7.

Table 4: Costs and schedules of recommended space astronomy missions (in alphabetical order; see Chapter 5 for prioritizations and categorizations). Costs are all in Canadian 2020-dollars unless otherwise specified. Future costs are estimates only and are subject to change.

Mission	***Anticipated Cost to Canada[39]***	***Participating Agencies (lead listed first)***	***Anticipated Launch Time Scale***
CASTOR	$250M-$400M	CSA, ISRO, JPL? UKSA?	late-2020s
JWST	TBC[40]	NASA, ESA, CSA	late 2021
LiteBIRD	$25M-$40M	JAXA, ESA, NASA?, CSA	late-2020s
NASA Flagships	Hardware: ~$100M Science, Technical: TBD	NASA, ESA?, CSA	mid-2030s
SPICA	$30M-$50M	ESA, JAXA, CSA, NASA?	early-2030s
POEP	$15M[41]	CSA	mid-2020s

[37] We do not address in this Chapter the opportunities provided by commercial satellites, since no specific proposals relating to such opportunities were made to the LRP2020 process. A broader recommendation on future involvement in commercial satellite programs is made in Chapter 7.
[38] except for NASA Flagships, which are discussed together
[39] Costs represent approximate total life-cycle costs (i.e., development, construction, launch, operations and science).
[40] Support for the operations phase over the nominal JWST mission lifetime of five years; does not include costs incurred so far.
[41] This does not include the launch costs, which are expected to be a small increment on the total cost.

ARIEL

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) is an approved medium-class space astronomy mission led by the European Space Agency (ESA). ARIEL will be a 1-metre telescope designed to obtain precise transmission spectroscopy over 0.5-7.8 micrometres for a large number of transiting exoplanets with hydrogen-rich atmospheres, from hot Jupiters to warm sub-Neptunes. It is scheduled for launch in 2028 and will be stationed at the Earth-Sun system's second Lagrange point ("L2"). During its 4-year mission, ARIEL will study the composition of exoplanet atmospheres and characterize their chemical gradients, structure, diurnal and seasonal variations, clouds, and albedo. ARIEL will observe about one thousand diverse exoplanets, and is highly complementary to JWST that will realistically characterize only dozens of planets in its lifetime. A large sample is essential to understand the huge diversity of exoplanet atmospheres, how exoplanets form, and how they evolve. ARIEL is the only mission designed for and dedicated to performing a spectroscopic survey of a large, well defined sample of exoplanets. The ARIEL mission is of great interest to the Canadian exoplanet community, supplementing and supporting many of their ongoing and future projects. The mission is complementary to the POEP program (see below), which is planned to launch on a similar timescale.

The ARIEL consortium recently approached Canadians to convey their interest for Canada to join and contribute to the mission. A hardware contribution for one of two subsystems well matched to Canadian industry was proposed (the cryoharness or the AIRS detectors), as well as a contribution of the software pipeline. The cost of the hardware contributions is on the order of $5M and $15M, respectively. The Canadian industrial expertise to contribute these hardware components was developed and proven in building the NIRISS instrument for JWST. The cost for a software pipeline contribution is estimated to be about $3.5M.

Currently there are three Canadian faculty-level members in the ARIEL consortium. Going forward, community participation can be expanded through an open process should Canada join and contribute financially to the mission. We encourage participation in ARIEL as a complement to JWST, as part of a community roadmap on exoplanets, and as a science pathfinder for future missions.

ATHENA

The Advanced Telescope for High-ENergy Astrophysics (ATHENA) was selected by ESA in 2014 as a large-class mission, for launch in 2031. ATHENA is an X-ray telescope with an effective collecting area of ~1.4 m^2 at an X-ray energy of 1000 electronvolts. Its two instruments include an X-ray integral field unit spectrograph (X-IFU), and the Wide-field Imager (WFI) for imaging and moderate-resolution spectroscopy over a large field of view. The primary science objectives for ATHENA are to map hot gas structures and determine their physical properties, and to search for and characterize supermassive black holes. Although Canadian involvement in Athena was prioritized in MTR2015, little progress has been made in determining any potential contribution. Thus while we encourage interested Canadian researchers to participate in this mission, there is not a case for a national contribution.

Ballooning

Stratospheric balloons offer near-space observing conditions for around 1% of the cost of an equivalent satellite, while also providing a platform to advance the technology readiness level of key systems for future space astronomy missions. Furthermore, balloon astronomy offers outstanding training opportunities: typical experiment timeframes allow graduate students to play a key role in instrument design, field campaigns, and scientific data analysis over the course of their degree.

The CSA's Stratospheric Balloon program (STRATOS) has provided launch opportunities to over 24 Canadian scientific balloon payloads since its beginning in 2012. Balloon launch support is provided by the Centre national d'études spatiales (CNES) of France, through a cooperation agreement with the CSA. Most of the launches that CNES has provided took off from Timmins, Ontario. However there have also been STRATOS launches from Kiruna, Sweden (2016) and Alice Springs, Australia (2017). The time in the stratosphere for these flights has ranged from 10 hours to several days. For projects with US collaborators funded by the National Aeronautics and Space Administration (NASA), flights are also available through NASA's Columbia Scientific Balloon Facility (CSBF) from a variety of locations, including long duration (weeks long) flights from Antarctica.

Since 2011, funding for stratospheric balloon borne payloads has been provided by the CSA's Flights and Fieldwork for the Advancement of Science and Technology (FAST) program. There have been six completed calls for proposals. For balloon payloads involving a launch within the period covered by the award, the maximum total funding available over the course of a three-year award has ranged from $100k to $500k. Of this funding, a significant fraction of the award is meant to be devoted to training highly qualified personnel, including undergraduate and graduate students, postdoctoral researchers, and other trainees. Multiple Canadian institutions may apply to FAST for the same project as long as the individual roles are clearly defined. Even so, this level of funding is adequate for a Canadian contribution to a multinational collaboration, but is insufficient to support an entire Canadian-led balloon project.

Within this context, there have been several highly successful balloon experiments with substantial Canadian involvement over the last decade, including the Balloon-Borne Large Aperture Sub-mm Telescope for Polarimetry (BLASTPol), the E and B Experiment (EBEX), the High Contrast Imaging Balloon System (HiCIBaS) and the Spider cosmic microwave background experiment. Current and upcoming projects supported by FAST include the Super pressure Balloon-borne Imaging Telescope (SuperBIT) plus its planned successor GigaBIT, the next-generation BLAST Polarimeter (BLAST-TNG), the Primordial Inflation Polarization Explorer (PIPER), and the High Energy Light Isotope eXperiment (HELIX).

To maintain leadership in astrophysical ballooning over the next decade, the Canadian astrophysical ballooning community has identified the following priorities:

- Continued support for HQP training and technology development;
- Gaining access to flights of several month durations using NASA's super-pressure balloon technology;
- Competitions to fund Canadian university groups to lead large experiments;
- Support for development of balloon gondolas and flight infrastructure systems that can be used by multiple experiments.

The LRP2020 panel notes the crucial technological, strategic and training benefits of balloon-borne astrophysics, and encourages the CSA to work with the ballooning community to achieve the above goals.

CASTOR

The Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) is a proposed Canadian-led 1-metre space telescope designed to provide both imaging and spectroscopy in the ultraviolet/optical spectral range (0.15-0.55 micrometres). Imaging with ~0.15-arsecond resolution will be obtained simultaneously in three passbands: UV (0.15–0.30 micrometres), u' (0.30–0.40 micrometres) and g (0.40–0.55 micrometres) over a 0.25-deg^2 field of view. The corresponding survey speed of CASTOR in ultraviolet/optical imaging will exceed that of the Hubble Space Telescope by roughly two orders of magnitude. In addition, the proposed spectroscopic capabilities for CASTOR include a multi-object digital micro-mirror spectrograph, providing moderate to high-resolution ultraviolet spectroscopy, and a grism mechanism yielding full-field, low-resolution spectroscopy in the UV and u' channels.

Finally, a single detector placed in each of CASTOR's focal planes will allow precision photometric monitoring of bright exoplanet hosts.

CASTOR has the potential to make transformational advances across a wide range of fields, probing the physics of star formation from our galaxy to the distant Universe through spatially-resolved ultraviolet/optical imaging, exploring the atmospheres of exoplanets through transit spectroscopy and photometry, improving constraints on dark energy through weak lensing measurements, studying the properties of the outer solar system through the discovery and study of small bodies, and localizing and following up electromagnetic counterparts to sources detected by gravitational-wave observatories.

CASTOR has been conceived as a CSA-led project. At the same time, international contributions are highly valued as they strengthen Canada's international ties, bring additional scientific and technical expertise to the project, and reduce the cost to Canada, making it possible to consider a mission of greater scope. Likely international partners include India (through the Indian Space Research Organization, ISRO), as well as JPL/Caltech/NASA. Other international partners potentially include the UK Astronomy Technology Centre and Laboratoire d'Astrophysique de Marseille (LAM) in France. The total mission cost for CASTOR with only imaging capabilities is estimated at around $400M; this includes launch and contingencies but excludes science support (~$20M). Adding the two spectroscopic modes mentioned above would add approximately $30M.

The highest recommendation from LRP2010 for Canadian Space Astronomy was for significant Canadian involvement in either Euclid or WFIRST (now renamed the Roman Space Telescope), or the development of a Canadian Space Telescope. The former has not come to pass. CASTOR would represent the long-awaited fulfillment of the latter, and a chance to revitalize Canada's space astronomy sector. The proposed timeline for CASTOR is as follows: a 12-month Phase A study (establishing system requirements) could begin as early as mid-2021. Phase B and C studies (i.e., preliminary and critical design reviews, respectively) would require 30 months. Fabrication, integration and testing (Phase D) would require approximately two years. Launch followed by the 60-month Phase E (operations) would thus occur in the late 2020s. This operational period would overlap with both LSST and the Roman Space Telescope, and possibly the final years of the Euclid and JWST missions. The baseline mission lifetime for CASTOR is a minimum of 5 years, and it would operate in a low-earth, sun-synchronous, dawn-dusk orbit, at an altitude of 800 km.

To maximize CASTOR's prospects of success, a development path for such large projects will need to be established within Canada, as part of a predictable and well-defined process for selecting, funding and maintaining a portfolio of major CSA science missions. In order to play the leadership role envisaged, the CSA must also secure the backing of international partners, whose interest in this project is high but who will soon need a clear commitment from Canada.

Recommendation: We recommend that the Cosmological Advanced Survey Telescope for Optical and ultraviolet Research (CASTOR) be approved for development toward launch. The CASTOR mission is a mature concept that has a world-leading and transformational science case, strong and long-standing community support, substantial interest and involvement from Canadian industry, and enthusiastic international partners who are looking to Canadian leadership to develop and fly a wide-field ultraviolet space telescope. CASTOR will also provide a superb complement to JWST and other forthcoming optical and infrared facilities. A top priority in MTR2015, CASTOR continues to be an outstanding prospect for Canada's first marquee space astronomy mission. It will be vital to engage with the federal government to fund this very large mission, and to work closely with international partners like JPL/NASA and IIA/ISRO.

Colibrì

Colibrì is an X-ray telescope currently in the concept study phase. Colibrì will boast high spectral resolution, high throughput, and large effective area over the energy range 200-20,000 electronvolts (2000 cm^2 at 6400 electronvolts). Colibrì offers a similar energy resolution to the gratings on Chandra and XMM-Newton and to the bolometers on Hitomi, but with ten times the effective area of these missions. It is also envisioned to provide high time resolution, better than 1 microsecond, matching the innermost orbital period for a 10 solar-mass black hole. Key science goals for Colibrì include studying the structure of accretion flows in the vicinity of black holes and neutron stars, and the study of emission from the surfaces of neutron stars. It will also investigate the nature of spacetime around black holes, the physics of jet launching, and the properties of ultra-dense matter.

Colibrì is a Canadian-led mission concept, drawing on most of the Canadian high-energy astrophysics community. Potential additional partners include NASA for mirrors and transition-edge sensor (TES) detectors, the US National Institute of Standards and Technology (NIST) for TES detectors, the Canadian Light Source for testing and calibration, and NASA/ESA for launch. In early 2020, Colibrì completed an 18-month concept study funded by CSA, with Honeywell and MDA as industrial partners. The recommendations the team presented to the CSA as the path forward for continued development of the mission included a science maturation study and a number of technology studies which would increase the capacity of the Canadian aerospace industry, as well as further mission goals. The total estimated cost of Colibrì is $1.34B, including launch, with an estimated launch date of December 2032.

We encourage further study of Colibrì through the CSA's development time lines and funding schemes, accompanied by relevant science and technology development studies and the continued development of the required international partnerships.

ÉPPÉ

The Extrasolar Planet Polarimetry Explorer (ÉPPÉ) is a proposed concept for a microsatellite mission that would use time-resolved differential polarimetry to characterize known exoplanets (hot Jupiters, Neptunes, super-Earths) and serve as a pathfinder for spectropolarimetric exoplanet biomarker detection. In contrast to current follow-up methods, polarimetry is equally well-suited to studying non-transiting exoplanets, preferentially around brighter stars. The differential polarimetry capabilities of ÉPPÉ would be uniquely sensitive to polarized scattered light from dust, clouds, and haze, enabling characterization of planetary surfaces and atmosphere content. To date, ground-based polarimeters have struggled to reach the 1 part-per-million level of precision required to detect scattered light from an exoplanet. The notional ÉPPÉ concept consists of a polarimetry instrumentation payload with a 30-cm aperture telescope operating in the 300-800 nanometre band from a 180-kg class spacecraft, somewhat larger than a typical microsatellite. ÉPPÉ would use Magellan Aerospace's new MAC-300 satellite bus design. A Sun-synchronous low-Earth orbit would enable on-target stares for up to two months. The CSA-funded concept study for ÉPPÉ was completed in late 2019. The projected cost of the mission, estimated at $40M-45M without launch, is moderately high for a microsatellite, and technical and scientific risks remain significant. Given these risks, the current level of maturation, the moderately high cost, and the short-term preference for POEP (see below) in these science and mission size categories, it is too early to recommend ÉPPÉ as a community-wide priority; however, we encourage further development of the ÉPPÉ mission concept.

Euclid

Euclid is an ESA-led 1.2-metre diameter space telescope selected in October 2011, with launch planned for 2022. The Euclid Mission aims to survey over 15,000 deg^2 of the extragalactic sky with imaging in a wide visible (riz) band at 0.1-arcsecond resolution, near-infrared photometry (Y, J, and H) and near-infrared spectroscopy.

The goals of the Euclid mission include understanding why the expansion of the Universe is accelerating and the nature of the dark energy seemingly responsible for this acceleration. The imprints of dark energy and gravity will be tracked by Euclid using two complementary cosmological probes to capture signatures of the expansion rate of the Universe and the growth of cosmic structures: weak gravitational lensing and galaxy clustering. Although low-redshift cosmology is the primary driver of the mission, a wide range of science, from the formation and evolution of galaxies down to the detection of brown dwarfs, will be possible with the Euclid near-infrared imaging data set, which includes broadband visible images and near-infrared photometry of roughly 1.5 billion galaxies and near-infrared spectroscopy of roughly 25 million galaxies.

Canada joined the Euclid Consortium in 2016, when CFHT approved CFIS as a Large Program. CFIS, along with other ground-based surveys, will be used by Euclid to measure photometric redshifts in the northern sky. 27 faculty-level astronomers in Canada are members of the Euclid Consortium. Such participation requires research support for science team members. We encourage inter-agency discussions (CSA, NSERC, NRC) on co-funding such opportunities.

JWST

The James Webb Space Telescope (JWST) is a 6.5-metre infrared-optimized space telescope, currently scheduled to launch to L2 in October 2021. JWST's four unique science instruments promise unprecedented sensitivity and transformative impacts for a broad range of astrophysical questions: JWST will trace the expansion history of the Universe, probe cosmic conditions at the epoch of reionization, reveal the formation and assembly of galaxies, identify the progenitor stars of supernova explosions, study proto-planetary systems and the ancient history of our own solar system, characterize the atmospheres of exoplanets, and establish the potential habitability of Earth-like temperate worlds. Capabilities include imaging plus slit, slitless, and integral-field unit (IFU) spectroscopy, and cover the wavelength range 0.6 to 28 micrometres. The mission is designed to last at least 5 years with a maximum of 11 years, limited by the propellant needed to keep the telescope in orbit. JWST is currently in its final phases of integration, with at least a 6-month launch delay resulting from the COVID-19 pandemic.

JWST represents an international partnership led by NASA, in collaboration with the European Space Agency and the CSA. Canada's substantial hardware contribution to the JWST project comprises the Fine Guidance Sensor (FGS) and the Near-Infrared Imaging and Slitless Spectrograph (NIRISS), included in the same instrument module. Canada will also play a leading role in early JWST science, with its leadership of both the CAnadian NIRISS Unbiased Cluster Survey (CANUCS) and NIRISS Exploration of the Atmospheric diversity of Transiting exoplanets (NEAT) 200-hour guaranteed-time observation (GTO) programs for the NIRISS instrument team; and a 30-hour Early Release Science (ERS) program to observe prototypical photo-dissociation regions with imaging and IFU spectroscopy using the NIRCAM, NIRSpec, and MIRI instruments. In addition, Canada is guaranteed at least 5% of the General Observer time (averaged over the long term).

Canada's involvement in JWST has been enabled by a significant (~$180M) investment from the CSA. This large commitment is consistent with the fact that the Canadian astronomical community ranked JWST first among space astronomy missions in the previous two LRPs, and recognizes the importance of this mission to the future of broad areas of astronomy.

Recommendation: We recommend that the CSA maintain financial support to the JWST mission and associated Canadian science for the entirety of the observatory's lifetime. Canada has already made a very large investment in this project, and continued support will leverage this investment for the highest possible science yield.

LiteBIRD

The Light satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is a planned millimetre-wavelength space telescope scheduled for launch to L2 in the 2020s for three years of observations. LiteBIRD covers 15 bands between 34 and 448 gigahertz, and its focal plane detector consists of a multichroic superconducting detector TES array with ~3000 bolometers. LiteBIRD detects polarization using half-wave plates. It will provide all-sky polarization measurements of the cosmic microwave background on large angular scales, which complement the higher-resolution, deeper yet partial maps of the cosmic microwave background from future ground-based experiments such as CMB-S4.

The key scientific goal of LiteBIRD is to search for the signals of inflation, specifically through the detection of B-mode patterns in the map of cosmic microwave background polarization. Such B-mode patterns are understood to be sourced by primordial gravitational waves that arise during the cosmic inflationary epoch (10^{-38} sec after the beginning of the Universe). LiteBIRD will test representative theories of inflation (e.g., single-field slow-role models with large field variation).

LiteBIRD is a Japanese-led project with collaboration between Japanese, US, European and Canadian groups, and was selected by JAXA's Institute of Space and Astronautical Science in June 2019 for launch in the mid-2020s, and a planned mission lifetime of three years. LiteBIRD was also identified as the top priority for Canadian cosmic microwave background science in MTR2015. LiteBIRD is enabled by key technology breakthroughs, including a novel Canadian TES multiplexed readout system that has been demonstrated in many of the world's ground-based cosmic microwave background observatories, and which is planned for deployment in CMB-S4. This Canadian technological contribution is already baselined for the mission, enabling Canadian access to LiteBIRD data. Canadian contributions are being studied through Science Maturation Studies and Mission Contribution Studies from the CSA. This project has entered Phase 0, and in order to ensure Canadian participation in this collaboration it requires a funding commitment from the CSA. The estimated cost for CSA is $25M-45M. The project carries potential risks in that deploying millimetre-wave TES detectors in space is unprecedented. However, the potential science returns considerably outweigh such risks.

Recommendation: We recommend Canadian participation in the Lite satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD). This participation should correspond to the complete life cycle of LiteBIRD, including hardware, mission operations, and science analysis. By focusing on the polarization of the cosmic microwave background at large angular scales, LiteBIRD will be an excellent complement to the ground-based CMB-S4 facility, and will provide an outstanding opportunity for Canadian cosmologists to make unique discoveries.

NASA Flagships

NASA develops space astronomy missions at a range of scales. The very largest missions, with budgets typically in excess of US$1 billion, are the large strategic space science missions usually referred to as "flagships". Current and upcoming flagships include the Hubble Space Telescope, Chandra X-ray Observatory, James Webb Space Telescope and Nancy Grace Roman Space Telescope.

Four new proposed flagship astrophysics missions, HabEx, LUVOIR, Lynx, and Origins, have been proposed to the US Astro2020 decadal survey. The report from Astro2020 will recommend which of these flagship mission(s) to pursue, and Canadian preferences will not influence those decisions. Canadian astronomers have expressed interest in participating in all of these missions.

Specific comments on each proposed flagship are as follows:

- **HabEx:** The Habitable Exoplanet Observatory (HabEx) is a mission concept for a 4-metre off-axis space telescope with coronagraphic and spectroscopic capabilities, whose main objective will be to directly image habitable Earth-like planets around sun-like stars, to characterize their atmospheres, and to look for signs of life. The science uniquely enabled by HabEx is exciting to both astronomers and the general public, representing a critical step in humanity's quest to understand the origins of life and its prevalence elsewhere in the Universe. In addition to its main objective, HabEx will enable a broad portfolio of studies in various other areas of astrophysics, and will be of high interest to many Canadian astronomers. Canadians have a strong heritage in high-contrast imaging observations and instrumentation, and have developed expertise valuable for a space astronomy mission like HabEx through contributions and technology development for JWST. We encourage Canadian astronomers to contribute scientific and technical expertise to HabEx should it be selected.

- **LUVOIR:** The Large UV/Optical/IR Surveyor (LUVOIR) is designed as a 15-metre diameter ultraviolet/optical/infrared space telescope**.** As a general-purpose large multi-wavelength space observatory, LUVOIR would enable transformational science across many areas of astronomy, from characterizing the icy geysers on large moons of our solar system to determining the nature of circumstellar disks and habitable exoplanets; from constraining the nature of dark matter on galactic scales to measuring the multi-phase structure of gas flows into and out of galaxies. The substantial Canadian contributions to JWST pave the way for a significant contribution to LUVOIR. If LUVOIR is selected for development by NASA, we encourage Canadian contributions to this mission, identifying the same areas of Canadian strength as for HabEx and JWST and potentially leveraging experience with CASTOR.

- **Lynx:** The Lynx X-ray Observatory will continue the revolution in X-ray astronomy started by the Chandra X-ray Observatory and XMM-Newton Observatory, by offering significant gains in imaging and spectroscopic sensitivity over the 100-10,000 electronvolt energy range. Major scientific programs planned for Lynx will include tracking the formation and growth of supermassive black holes over cosmic time, revealing the hot gas ejected by stars and galaxies into their surroundings, studying the many different ways in which stars violently end their lives, and probing the extreme physics of exotic compact objects such as neutron stars and X-ray binaries. Canadians have published more than 400 scientific papers using data from Chandra and XMM-Newton. Furthermore, the Canadian high-energy astrophysics and quantum materials communities have developed the mission concept for Colibrì (see above), which shares scientific goals and capabilities as well as key technologies with Lynx. Canadian technology and scientific studies for Colibrì, Hitomi and XRISM set the stage for a substantive Canadian contribution to Lynx.

- **Origins:** The Origins Space Telescope is conceived as a mid- and far-infrared 5.9-metre diameter telescope, providing imaging, spectroscopic, and polarimetry observations. Owing to its wavelength coverage and unprecedented sensitivity, Origins would enable transformative studies on most areas of astronomy, including the birth and evolution of galaxies, the growth of supermassive black holes, the production of heavy elements, the formation of star and planets, and the cycle of water and other life ingredients and their implications for habitable worlds. Origins would offer a spectacular improvement over the Herschel Space Observatory in both sensitivity and angular resolution. Canada made significant contributions to two of the three instruments on Herschel, and Canadians made many discoveries with the ensuing data. We anticipate similar extensive use and output from Origins if this mission goes ahead. It is currently too early to identify any specific role for Canada in this mission, but the fundamental goals and instrumentation requirements are very similar to those for SPICA, which we recommend as a priority below. Continued involvement in SPICA can position Canada for a potential role in Origins at a later date.

There are two potential routes for Canadian participation in any selected NASA flagships. In one route, Canada participates in the scientific and technical aspects of such a mission, but without making a hardware contribution. A second, more ambitious route, involves Canada contributing significant hardware (on the order of $100M, similar to our participation in JWST), in addition to scientific and technical contributions. The former route would be achievable through existing CSA programs and budgets; the latter route would require significant additional funding.

Recommendation: We recommend that the CSA provide funding that enables Canadian scientific and technical participation in preparatory activities for the NASA flagship mission(s), through design reference missions, analysis software, instrument design, science teams, working groups, etc. Any such opportunities should be disseminated widely, and appointments made by CSA should take place through an open and competitive process. These scientific and technical contributions should be pursued as soon as circumstances allow.

Recommendation: We recommend that Canada contribute ~$100M in hardware to a flagship astrophysics mission selected by NASA. However, such a hardware contribution should be regarded overall as a lower priority than investing in CASTOR, LiteBIRD and SPICA at the recommended levels. A significant hardware contribution to a NASA flagship astrophysics mission would strengthen Canada's standing as a strong international partner in space astronomy. Ahead of CASCA's midterm review in 2025, Canadian astronomers should work with the CSA and industrial partners to identify potential hardware contributions to the selected NASA flagship(s) and, where appropriate, the CSA should support technology development studies. The 2025 midterm review would then be in a good position to provide guidance on an eventual contribution to a flagship mission.

NEOSSat

The Near Earth Object Surveillance Satellite (NEOSSat), launched in 2013, has played an important role in maintaining Canadian technical capabilities in small-satellite space science. NEOSSat's imaging can be used to conduct photometric studies with precision sufficient for asteroseismology studies and other variability analyses of stars and exoplanet systems; it has already demonstrated imaging and photometry of exoplanet transits. NEOSSat is well-suited for the study of near-Earth asteroids or comets as it provides near-Sun observing capabilities and can provide direct parallax measurements of nearby objects due to its orbit around Earth. NEOSSat's first science guest observer program in 2019 was heavily oversubscribed, and recent NEOSSat imagery has demonstrated high-precision photometry on bright stars with exposure times of a few seconds. We encourage the CSA to monitor the demand for and outcomes of this program, and to adapt their support accordingly.

POEP

Photometric Observations of Extrasolar Planets (POEP) is a fully Canadian small-satellite mission whose main science objectives are characterizing known transiting extrasolar planets and discovering new ones. The baseline mission concept is a 15-centimetre space telescope on the well-tested MSCI multi-mission satellite bus with legacy from MOST and NEOSSat. The telescope would feed two frame-transfer charge-coupled devices (CCDs), in u-band and i-band, to obtain high duty cycle imaging and precise photometry. The spacecraft would be placed in an 800-kilometre Sun-synchronous orbit. The payload will have a continuous viewing zone between approximately -20° and +30° in declination, and will be capable of staring at a single field for up to two months. In Fall 2019, the mission concept completed a science maturation study funded by the CSA. The estimated total cost is $15M, including operations but excluding launch. A launch is possible as soon as 2025, with a minimum mission lifetime of two years.

POEP's transit depth measurements of known transiting exoplanets in both u and i bands will reveal the extent of their atmospheres and probe the presence of clouds and aerosols, improving our knowledge of exoplanet fundamental parameters and establishing a legacy of long-term precision timing of transit events useful for spectroscopic follow-ups. The POEP mission will uniquely complement a number of current, confirmed or proposed space-based facilities including TESS, CHEOPS, JWST, CASTOR, PLATO and ARIEL. For example, JWST and ARIEL will provide spectroscopic observations in the infrared to study molecules in exoplanet atmospheres. As clouds limit the depth to which an atmosphere can be probed using techniques such as near-infrared transit spectroscopy, the interpretation of these observations will require the understanding of the potential presence of clouds provided by POEP.

Precision i-band photometry with POEP will allow the detection of small, potentially rocky and habitable transiting exoplanets around ultra-cool dwarf stars. These faint, very red low-mass stars and brown dwarfs remain beyond the photometric grasp of TESS. However, because of favourable planet-to-star flux ratios, any planets orbiting them would offer some of the best opportunities for atmospheric characterization and biosignature detection with JWST or with a ground-based VLOT.

Beyond the field of exoplanets, the dual-band capability of POEP will also allow studies of the size-distribution of small bodies in the solar system through occultation measurements, hot white dwarfs in close or interacting binaries, the flaring properties of M dwarfs, and stellar pulsations, interiors and evolution.

Small-satellites present an effective and low-cost platform for rapid technology and methodology innovation that complements larger missions. As experience has shown with MOST and BRITE, the science impact of such missions per dollar invested compares very favorably to many major ground- and spaced-based facilities. Small-satellite missions also present an excellent opportunity to train and sustain a robust, experienced workforce within the space sector, which will provide a platform for larger Canadian-led space astronomy missions in the future. Given the strong heritage on which POEP builds, its technical risks are relatively low.

Recommendation: We recommend development of the Photometric Observations of Extrasolar Planets (POEP) mission. The goal should be to enable a launch in the 2025 timeframe, to allow follow-up of exoplanet discoveries made with TESS and CHEOPS, and to provide significant overlap with complementary future space astronomy missions such as JWST, ARIEL, PLATO and CASTOR. POEP has the potential to provide high science impact on exoplanets and the outer solar system for a relatively small investment, and will allow Canada to maintain leadership in small-satellite astronomy.

SPICA

The Space Infrared Telescope for Cosmology and Astrophysics (SPICA), led by ESA and JAXA, is a mission concept for a 2.5-metre diameter telescope, cooled to a temperature below 8 kelvin for deep mid- through far-infrared imaging and spectroscopy over a field of view of 30 arcminutes. SPICA will exploit detectors boasting factors of 2-3 orders of magnitude more sensitivity than any flown on previous infrared space missions. Instead of liquid cryogens, a combination of passive and mechanical coolers will cool both the telescope and instrument suite: no longer dependent on a limited consumable, the mission lifetime may extend significantly beyond the nominal three years. This combination of low telescope background and instruments employing state-of- the-art detectors will allow SPICA to bridge the gap in capabilities between JWST and ALMA, and represents a major advance in capability over previous far-infrared missions.

The SPICA instrument suite consists of three independent instruments: SAFARI – a far-infrared spectrometer, SMI – a mid-Infrared camera and spectrometer, and B-BOP – a far-infrared imaging polarimeter. Together, these instruments provide a range of spectral resolutions optimized for many scientific experiments. Additionally, SPICA will be capable of efficient broad band mapping over the range 30-37 micrometres, and spectroscopic and polarimetric imaging in the 100 - 350 micrometre range.

In development since 2007, the SPICA mission was selected in May 2018 by ESA as one of three finalists for the next Medium class mission of the Cosmic Vision program, for an envisioned launch in the early 2030s. The ESA Mission Selection Review to pick the winner of the three M5 finalists is scheduled to be held in April 2021; this point will mark the last opportunity for any nation to enter the SPICA consortium. If selected by ESA in 2021, SPICA will undoubtedly be the leading infrared observatory of the next decade.

The mid- through far-infrared spectral region is an important indicator of how, where, and when the galaxies in the Universe emit energy. This wavelength regime is also abundant in spectroscopic diagnostics, including those from light molecules such as H_2 and HD, important for direct determinations of gas mass. This is also the most important part of the electromagnetic spectrum for observations of water, in both gas and ice form, and thus a key probe into the pathway to life around stars. Furthermore, a wealth of fine-structure lines probes the ionized regions around hot stars and active galactic nuclei -- providing essential diagnostics of temperature, metallicity, and hardness of the radiation field. Similarly, dust features manifest strongly in this window, including emission from polycyclic aromatic hydrocarbons (PAHs), silicates, minerals, and both crystalline and amorphous ices. When combined with the fine-structure lines, PAH and dust emission provide important diagnostics for the energy budget of galaxies. In this context, the enormous increase in sensitivity provided by the SPICA instrument suite will open up a vast and unique discovery space and enable transformational discoveries in the study of galaxy evolution across cosmic time, the baryonic cycle in nearby galaxies, star formation in galactic molecular clouds, the evolution of protoplanetary disks, and exoplanet atmospheres. SPICA will revolutionize our understanding of how the Universe, our Galaxy, our Sun, our solar system, and the Earth began and have evolved up to this point in time.

Thanks to sustained investment by CSA over the past decade, Canadian scientific, technical and strategic leadership in the SPICA mission is well established. As a founding member of the SPICA/SAFARI consortium, Canada not only has much greater visibility and influence on the project, but also has the opportunity to contribute high-profile flight hardware to the mission, namely the high-resolution spectrometer component of the SAFARI instrument, one of three critical components of SAFARI. The cost of this Canadian contribution is expected to be $50M-60M. The impact on Canadian science, in terms of return on investment by the involvement of Canadian astronomers in science exploitation with SPICA through access to guaranteed observing time, will be over twice that of Herschel, which was one of the highest returns on investment of any CSA-funded space astronomy mission.

Recommendation: We recommend Canadian participation in the Space Infrared Telescope for Cosmology and Astrophysics (SPICA). This will require both a commitment of funding for the currently identified Canadian contribution to SPICA, and confirmation from CSA of Canadian interest in SPICA participation in the context of the pending (April 2021) ESA downselect. The SPICA mission will leverage substantial Canadian heritage and leadership in infrared space astronomy, and can revolutionize our understanding of cold gas and dust throughout the Universe by providing unique access to far-infrared wavelengths.

XRISM

The X-ray Imaging and Spectroscopy Mission (XRISM) is an upcoming Japanese-led space astronomy mission centred on high-resolution X-ray spectroscopy, and aims to replace the capabilities lost through the failure of the Hitomi satellite in 2016. XRISM will host two X-ray instruments: Resolve (a microcalorimeter covering the energy range 300-12,000 electronvolts) and Xtend (a CCD imager covering 400-13,000 electronvolts). XRISM is scheduled for launch in 2022, with science programs centred on studying the chemical composition of the Universe, the motions of hot gas in galaxies and galaxy clusters, and the properties of white dwarfs, neutron stars and black holes.

Resolve and Xtend are being tested and calibrated using the Canadian Light Source in Saskatoon, SK. Canadian scientists will have access to XRISM observations in return for this contribution. Canadian scientists are also members of XRISM's International Science Team and of the Resolve Instrument Team. Building upon our success in contributing to the Hitomi mission, we encourage both continued Canadian participation in XRISM and further technological development for high-energy astrophysics.