

Unveiling the Cosmos

Canadian Astronomy 2016–2020

Report of the Mid-Term Review 2015 Panel





"The stars belong to everyone."

Helen Sawyer Hogg

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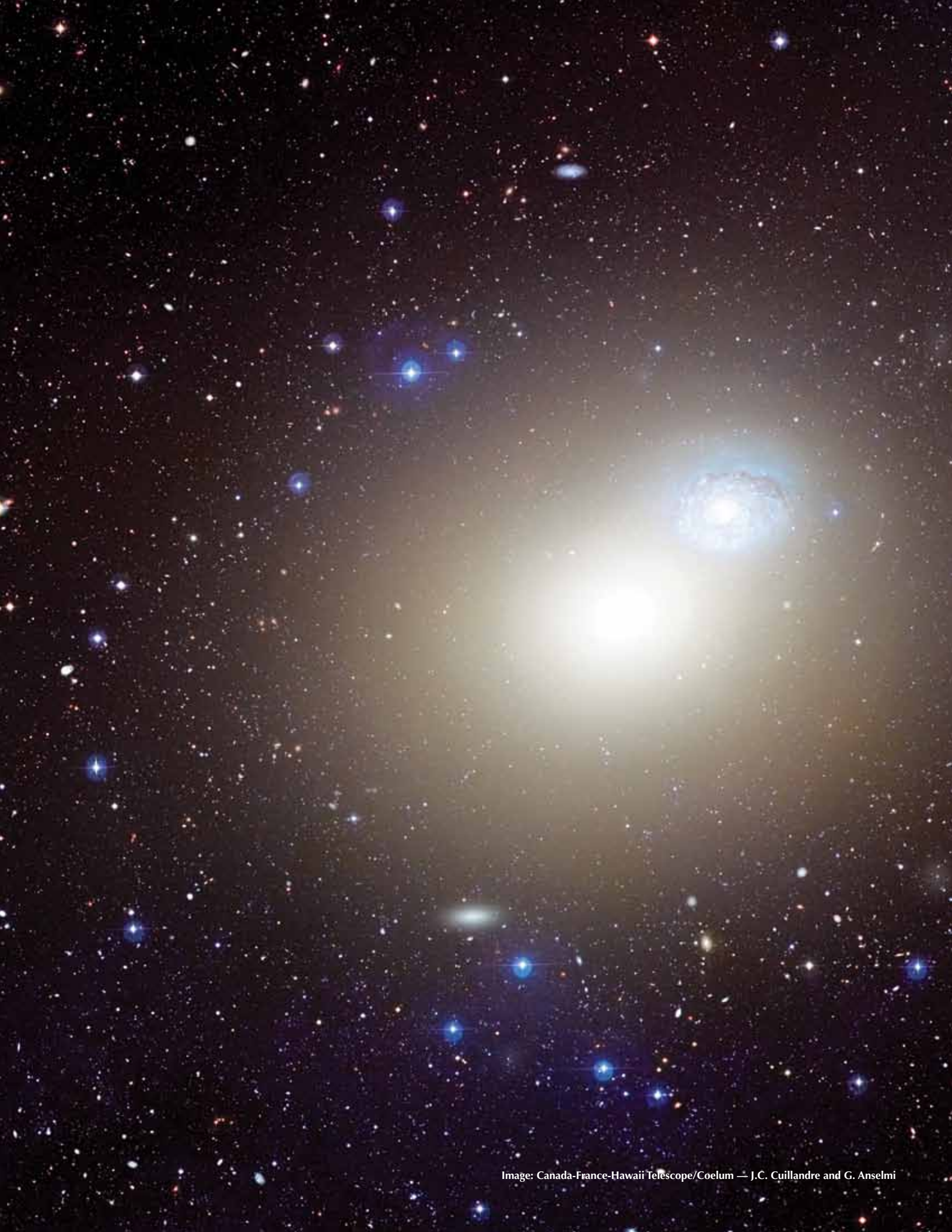
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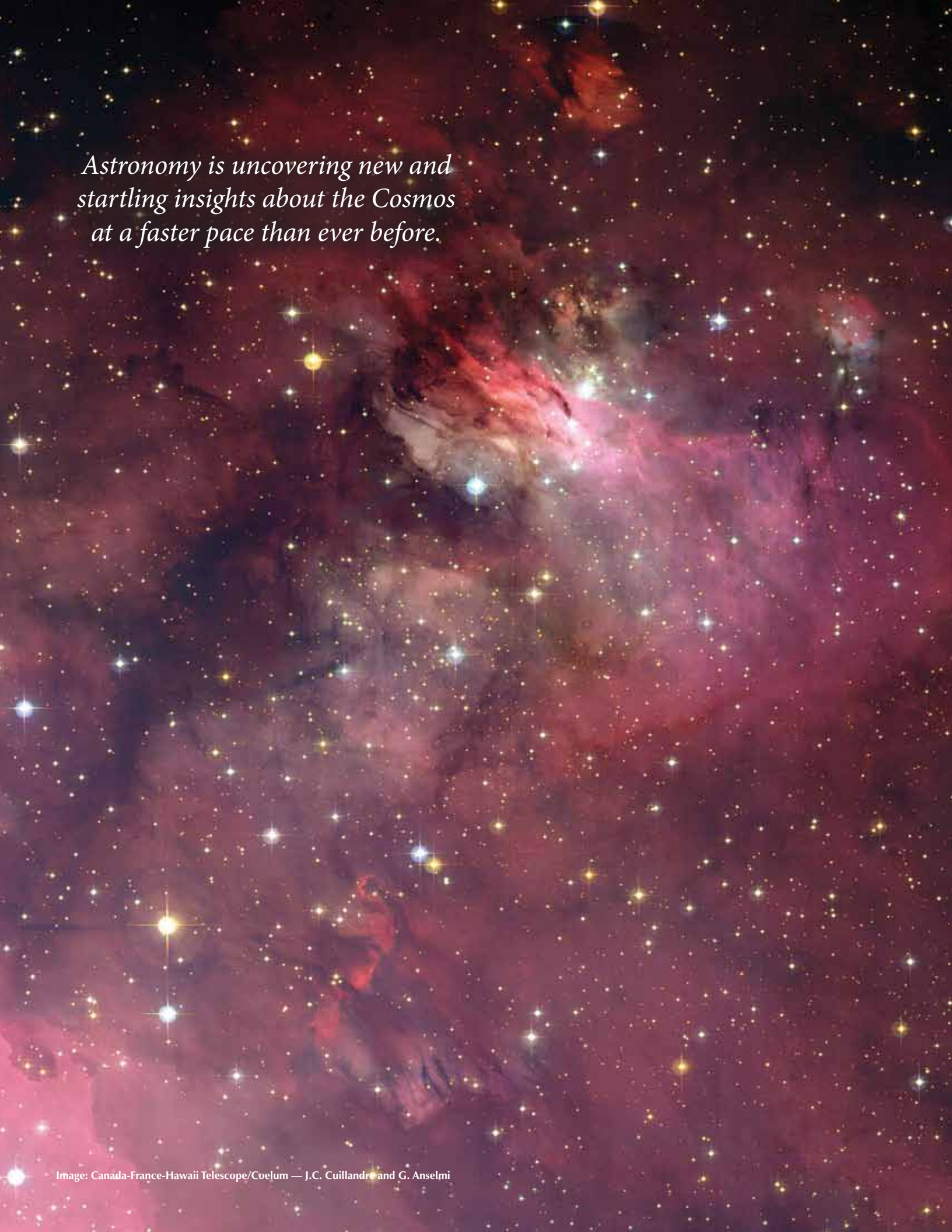
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*Astronomy is uncovering new and
startling insights about the Cosmos
at a faster pace than ever before.*

1 Introduction and Executive Summary

1.1 Introduction

Astronomy is uncovering new and startling insights about the Cosmos at a faster pace than ever before. Extrasolar planets are now known to be commonplace, and the possibility of detecting signs of life, biomarkers, occupies the thoughts of many researchers. Such measurements may be possible with the next generation of large aperture optical telescopes. Looking back to the Big Bang, we are now on the verge of measuring the impact of gravitational waves generated by quantum effects during the Inflationary epoch, an era when the Universe expanded at unprecedented rates. Aside from generating important new knowledge, modern astronomy both utilizes and creates technological breakthroughs, such as the research that brought us Wi-Fi. When all astronomy's influence is considered, it reaches from changing everyday life through new technologies to giving human civilizations a profound philosophical context.

Yet, for the grandness of accomplishments to date, there remain equally important fundamental questions about the formation and evolution of black holes, stars, planets, galaxies, and the Universe as a whole that remain to be solved. For many of these questions, the observations required push the development of new facilities and technologies, across a range of wavelengths.

These technology developments inevitably require close collaboration between the NRC, CSA, universities, and technology companies. Indeed, by far the majority of the funding involved in the construction of new astronomy facilities goes to industry. Analysis by independent consultants,¹ in government commissioned reports, suggests the measurable return on investment in astronomy is one-to-one. When indirect returns are considered, which are

notoriously difficult to quantify, the returns are higher. Neither do these metrics consider the social good inherent in new discovery, and the role it plays in inspiring young minds to consider careers in science and engineering.

Within Canada, the independent Science, Technology and Innovation Council (STIC) has authored a series of reports focusing on the role and current status of science and innovation in Canadian society. Heavily based upon these reports, government funding strategies have been developed that focus on the environment, health sciences, natural resources, information and communication technologies, and recently, advanced manufacturing. Astronomy, perhaps surprisingly, has influenced the development of all these priority areas. Arguably the most influence has been on information and communication technologies where the fundamental nature of astronomy as a sensing science continues to spur new developments therein. But the enhancement of technologies within astronomy, the charge-coupled device being a notable example, has influenced environmental science and natural resources through the delivery of detailed satellite imagery and analysis. Both laser eye surgery and X-ray imaging rely upon techniques initially developed within astronomy. The development of new and increasingly sophisticated astronomy facilities also promises steps forward in manufacturing processes. Thus despite commonly expressed prejudices that astronomy has little influence beyond the philosophical, its influence on society is remarkably pervasive and inherently practical.

1.2 Executive Summary

Canadian astronomy and technology have repeatedly driven scientific revolu-

tions that deliver spectacular new insights into our Cosmos, while simultaneously benefitting our society in multiple ways (See Chapter 4 Astronomy and Society). Almost 860 scientists are now involved in government funded astronomy research in Canada. Normalized citation metrics place Canadian astronomy either at, or close to, number one in the world. This excellence is enabled, in part, by the infrastructure the federal government and other public and private agencies have made available through direct investment or other vehicles.

This *Midterm Review (MTR2015)* works within the wider framework laid out by the 2010 *Long Range Plan (LRP2010)* “Unveiling the Cosmos” which developed a compelling and exciting decadal vision for Canadian astronomy. In the five years since LRP2010 significant changes have occurred in the research landscape; it is the charge of the MTR Panel (MTRP) to evaluate those changes against the priorities established by LRP2010. Driven first and foremost by priorities of scientific excellence, and maintaining Canadian astronomy's competitiveness in international astronomy, the planning process pays careful attention to priorities outlined within the Canadian government's science and technology strategy. The overall plan is highly coordinated, covering a breadth of science areas, funding of facilities on various scales, and maximizing science and technological return on investment. Withdrawals from older facilities, as new ones begin operation, are also advocated within the LRP process. It is also understood that revisions of recommendations may be necessary on short time-scales due to unanticipated events or developments. Established in 2010, the Long Range Plan Implementation Committee (LRPIC) is the body responsible for such oversight and it should continue its mission.

¹ Hickling, Arthurs, Low, “Astronomy in Canada” 2011

In the interests of brevity, this executive summary does not repeat all recommendations in detail. For clarity, a reference to the exact recommendation wording in the report body is provided. A complete table of recommendations is provided in Section 10.5 List of MTR2015 Recommendations.

World Observatories

Since LRP2010 was authored, construction of the Atacama Large Millimeter/sub-millimeter Array (ALMA) has been completed and the telescope is now yielding remarkable new results on systems from protoplanetary disks through to distant young galaxies. Canadian scientists are making excellent use of the facility, while the Canadian construction contribution, the “Band 3” receivers, is a key enabler of many of these science breakthroughs.

In the same period, the Canadian Government pledged \$243.5M that will allow Canadian industry, in collaboration with the NRC and universities, to design, develop and build a major contribution to the world’s premier optical facility, the Thirty Meter Telescope (TMT). This major investment will give optical astronomers in Canada access to the world’s premier observatory, quite literally bringing new worlds to Canadians. Currently a collaboration between Caltech, University of California, Canada, Japan, China, and India, the Canadian share of approximately 15% is lower than anticipated in LRP2010, but should still ensure that Canadians have a significant voice in the operation of the facility provided that we continue to contribute to new instrumentation projects. Motivated by this concern, *the MTRP therefore strongly endorses ongoing development of second-generation instrument concepts for the TMT and encourages the various teams to pursue funding* (page 27).

Looking forward to the 2016–20 period, *access to the capabilities provided by the first phase of the Square Kilometre Array*

(SKA1) is the top priority for new funds for ground-based astronomy (page 29). The SKA has evolved considerably since 2010. Firstly, the cost cap on the first phase (SKA1, approximately 10% of full capability) has been set at €650M, and a 2018 construction start is now planned. Secondly, the ten countries involved are now moving toward the development of a treaty governing the construction and operation. Canada, particularly through the NRC, has already developed innovative new technologies (see Section 5.1.2 SKA) for the SKA and can partner with Canadian industry to deliver these technologies at a cost of \$60M. The scientific promise and the potential for industrial involvement in the facility lead the MTRP to reiterate the importance of the project to the Canadian community. In support of this prior recommendation *the MTRP strongly recommends that Canada enter into negotiations to join the intergovernmental organization* (page 31) that will oversee SKA1 construction.

Ground-based Astronomy

Since 2010 the Gemini Observatory has installed a number of world-leading new instruments, including the Gemini Planet Imager. The operating partnership has changed following the withdrawal of the UK, and Australia’s announcement that it could not continue as a partner beyond 2015, although the Korean Astronomy and Space Science Institute will hopefully take over the Australian share in 2017. It is now clear that participation in the observatories beyond 2021 is necessary, *and the MTRP recommends that Canada’s participation in Gemini continue to be supported beyond the end of the 2016–21 International Agreement. The nature and level of that participation must be considered within the context of a coordinated plan for funding the operation of our ground-based facilities, together with any opportunities for broader access to the landscape of 8–10 metre optical/IR telescopes* (page 37).

The 3.6 m Canada-France-Hawaii Telescope (CFHT) continues to enable impressive new science. While the Mega-Cam imager is now only class-leading in one waveband, the facility continues to offer exceptional image quality and the potential for contributing imaging in support of a number of upcoming surveys. At the same time, exciting new instrumentation, including the SITELE imaging Fourier transform spectrometer and the SPIRou high resolution spectropolarimeter will open up new fields of discovery.

The “next generation” CFHT project has evolved into the Maunakea Spectroscopic Explorer (MSE) and the telescope design is now mature. A number of countries are participating in both science working groups and telescope engineering. Being an 11 m facility dedicated to multi-object spectroscopy, it has the potential to open up new realms of discovery across many fields, from stellar astronomy through to the nature of dark matter and dark energy. *The MTRP thus strongly recommends that Canada continue to lead the development of the MSE project* (page 35). *Further, while the MTRP fully supports the SPIRou project and planned surveys, it notes that any schedule slippage should not delay redevelopment opportunities and priorities* (page 33).

Highlighted in LRP2010 as a superb example of Canadian leadership, the CHIME telescope, funded by the CFI and provincial agencies, and located at the DRAO in Penticton, will begin operation in 2016. Built with a primary goal of placing constraints on dark energy, once operating it will be the largest single radio telescope facility (by collection area) in North America. Unanticipated in 2010, it will also incorporate a new analysis backend to search for radio transients such as “fast radio bursts”. The MTRP is excited to see first science results, and commends the working relationship between the NRC and universities on CHIME.

Following LRP recommendations, Canada withdrew from the sub-mm James Clerk Maxwell Telescope (JCMT) in September 2014. The facility has transitioned to operation by the East Asian Observatory with a collaboration of six Canadian universities working together to provide funding and some access for the entire Canadian community for 2015–16. Progress on funding the next generation Cerro Chajnantor Atacama Telescope (CCAT), one of the recommended midscale facilities in LRP2010, has not proceeded as expected, although the facility continues to offer exceptional promise, including mapping speeds tens of thousands of times faster than ALMA. *The MTRP reaffirms the importance of next generation single-dish sub-mm facilities, and recommends that Canadian astronomers continue to pursue participation in CCAT, subject to the project meeting its original science goals* (page 41).

The Large Synoptic Survey Telescope (LSST), the US astronomical community's top ranked ground-based project in their last decadal plan, is moving toward completion. While interest in Canadian participation in 2010 was nascent, as of 2016 there is now a partnership of Canadian universities, spearheaded by the Dunlap Institute at the University of Toronto, which will allow the participation of ten Canadian faculty, and their associated highly qualified personnel, in LSST. While the MTRP welcomes this development, and notes that LSST has considerable complementarity to MSE, there does not appear to be a straightforward route to broader Canadian participation at this time.

Instrumentation and Principal Investigator (PI) Facilities

A healthy research portfolio requires access to facilities at vastly different cost-scales. While by far the majority of ground-breaking results are made on world-leading facilities, actively-used supporting facilities also play an important role beyond training alone. They enable rapid

testing of innovative science ideas (transient science being a current example), provide a platform for building and testing instrumentation prototypes, and can also provide supplementary observations to large facilities. The analogy of a pyramid of infrastructure is apt in this case and *the MTRP reaffirms the importance of facilities across the spectrum of scales, including lower cost PI instruments* (page 20).

Space Astronomy

Observations from the ground with the TMT, SKA, and other instruments are complemented by space observatories. The Hubble Space Telescope (HST), for example, has changed our view of the Cosmos and become the most well-known scientific instrument in the public consciousness. The launch of its successor, the James Webb Space Telescope (JWST) in 2018, is eagerly anticipated by the world-wide astronomy community. With its 5% share of the telescope, Canada is well-placed to reap immense scientific returns and JWST remains the single largest investment in Canadian space astronomy. While participation in JWST marks a high point in Canada's commitment to space exploration and astronomy, there are significant areas of concerns about involvement in future missions. In the 2000–10 decade the Canadian Space Agency (CSA) committed to participating in seven missions, including ASTROSAT and JWST. In the five years since LRP2010, the only new large space mission which Canada has committed to is the Japan-led ASTRO-H X-ray telescope.

LRP2010's top recommendation for space astronomy was involvement in a survey mission that can shed new light on the mystery of dark energy. Driven by discovery potential and key technologies, the MTRP reaffirms this recommendation. Two missions present themselves at this time, the US-led WFIRST mission, the top priority in the US decadal plan, which is now moving ahead rapidly, and the Canadian-led CASTOR. The two

missions have distinctly different optical technologies making the science cases highly synergistic. Unfortunately, at the time of writing, CASTOR has not been given sufficient resources to fully cost its design, precluding a competitive evaluation of return on investment.

The MTRP sees the broad science case of the WFIRST mission as exciting, but notes that establishing sufficient Canadian participation remains a concern. *The MTRP thus reaffirms the exciting opportunity presented by WFIRST and its broad appeal to the Canadian community. In order to fulfil the LRPP recommendation we recommend that Canada begin negotiations to secure a significant (~5%) level of participation, at the earliest opportunity, so as to match NASA's accelerated schedule. This should include contributions to critical instrumentation that, preferentially, is synergistic with Canadian science interests, and funded participation on Science Investigation Teams for a representative number of Canadian scientists* (page 45). At the same time, *the MTRP strongly recommends that the CSA launch a Phase 0 study for CASTOR, with study results required within 12 months, so that this compelling project can be developed, presented, and competed in the international community. The LRPIC and Joint Committee on Space Astronomy (JCSA) should review the outcome of that study and make further recommendations as appropriate, well in advance of LRP2020* (page 46).

A highly topical science area, in which Canada has significant hardware and theoretical expertise, is measurement of the polarization of the Cosmic Microwave Background (CMB). Measuring the 'B-mode' polarization provides a direct constraint on the fraction of gravitational waves produced in the inflationary epoch of the Big Bang. This field has moved forward rapidly since LRP2010 and one or more upcoming missions are likely to fly in the early 2020s: PIXIE (US-led) and LITEBird (Japan-led, with NASA

participation). Given Canada's significant scientific and technological expertise in the field, *the MTRP strongly recommends that the CSA engage in discussions with its sister agencies to establish a hardware and science role in a new CMB polarization mission* (page 47). Moreover, the comparatively rapid development of these two missions means that significant funding is potentially needed within a one to two year time frame.

LRP2010 selected the International X-ray Observatory (IXO) and SPICA for support at the mid-range level. IXO evolved in a descoped form into the Athena mission, led by ESA, and will fly in 2028. While having exceptional promise, and with a capability that is arguably that of a “world observatory” for X-ray astronomy, a route to Canadian participation is unsure at this time. *The MTRP therefore recommends that Canada continue to explore the possibility of contributing to the science instrumentation on Athena, as well as the cost and the access to the mission that would be gained from such a contribution* (page 49). The SPICA mission has also undergone a descope and is now looking at a 2029–30 launch, with an exact determination of the launch window anticipated in 2016. Unfortunately, the descope removed one potential primary Canadian technology contribution although others remain. *The MTRP recommends that Canada explore the possibility of contributing elements of the Fabry-Perot instrument to SPICA, as well as the cost and the access to the mission that would be gained from such a contribution* (page 50). The long lead time to launch for both these missions means that sizeable investment will not be necessary until the 2020s.

Canadians have continued to make significant use of nanosatellites and balloon missions. The BRITE constellation and Balloon-borne Imaging Telescope (BIT) projects are key examples in each respective category. For both categories, innovative science continues to be accessible at launch costs considerably lower than as-

sociated with large-scale orbital platforms. *The MTRP recommends that Canada continue to support small-scale exploratory satellite projects and balloon-borne missions through regular calls for proposals* (page 51). Competitive funding processes, advertised at regular intervals, will continue to spur innovation in this sector.

Funding

Funding in support of astronomy from NSERC has fallen from \$11.8M in 2010 to \$11.0M. If inflationary rises are included the envelope should now be \$12.8M. In addition the loss of the Special Research Opportunities program and Major Resources Support program continues to have a great impact. Across the board, funding in support of astronomy science delivery, as opposed to hardware, is down since 2010. Consequently, *the MTRP recommends reinstating funding to support laboratories* (page 20) *and post-doctoral programs* (page 64), that will largely return NSERC funding levels to previous values. At the same time, *the MTRP reiterates that the creation of a network of post-doctoral researchers is critical to maximizing the significant investment that has been made in the JWST facility* (page 64) and other space astronomy investments. Equally importantly, in support of these observational developments, *the MTRP reaffirms recommendations for a moderate increase to the funding of the Canadian Institute of Theoretical Astrophysics (CITA) to augment the National Fellows program* (page 21), *and the value of a further funding cycle of the Canadian Institute for Advanced Research's Cosmology and Gravity program* (page 52).

Diversity in Astronomy

Women and minorities continue to be underrepresented in Canadian astronomy, with female participation within the faculty ranks now at 18%, although an accurate breakdown by rank is not possible without a complete survey. The cancellation of the NSERC University Faculty Awards

(UFA) program is regrettable in that approximately 40% of female astronomy faculty in Canada have been supported by it, or the earlier WFA program. Alternatives to funding faculty positions include career interruption support, changes in assessment of productivity, and also offering awards to institutions that take steps to support the participation of women and minorities in astronomy. *The MTRP thus recommends that CASCA's newly formed Diversity and Inclusivity committee should restart CASCA's equity survey process, extending it to capture data on minority participation. From the data derived, policy recommendations should be formulated that either the LRPIC or LRP2020 can directly build upon* (page 66).

Scientific Computing

Increasing visibility of data analytics, more commonly called “Big Data,” has renewed interest in funding computational and storage infrastructure. Through a series of newly announced CFI investments, Compute Canada (CC) will spend at an average of \$50 million per year in 2015–20, the value recommended in LRP2010. The service requirements of distributed computing platforms are growing *and the MTRP recommends that CC move to provide services such as authentication/authorization, and efficient distributed storage platforms that encompass both archiving and user spaces in a scalable way* (page 57).

The NRC's Canadian Astronomy Data Centre (CADC) continues to serve data to the astronomy community and is a major driver behind the innovative Canadian Advanced Network for Astronomical Research (CANFAR) project. CANFAR has evolved significantly in the last five years, and now sits at a transition point in terms of its hardware platform and governance. A serious concern exists over its future funding due to CADC staff being ineligible for support in university-NRC collaborative proposals to CFI, and *the MTRP recommends the Agency Committee*

on Canadian Astronomy meet to discuss this significant issue (page 58).

Astronomy Outreach

Uncertainties remain in terms of national coordination of outreach efforts, and the MTRP recommends that CASCA draft a mission statement on its EPO activities and goals (page 22). The MTRP also recommends that social media be considered a key part of any outreach strategy, with appropriate resources, specifically funds, talent, energy and time, allocated (page 23). The MTRP also supports augmentation of the NSERC PromoScience budget and that NRC Herzberg return to funding outreach at previous levels (page 23).

Astronomy Governance

NRC Herzberg (formerly Herzberg Institute for Astrophysics) continues to operate the observatories of the Government of Canada, and serves as the de facto national astronomy laboratory. However, the overall mission of the NRC has moved toward supporting industrial innovation making NRC Herzberg somewhat unusual within the entire NRC portfolio. In recognition of the close collaboration between NRC Herzberg and the university research community, that is essential to the success of Canadian astronomy, the MTRP recommends the re-establishment of an Advisory Board, drawn from university researchers and industry, to advise on the portfolio and programs of NRC Herzberg (page 60).

Conclusion

The future of Canadian astronomy is truly exciting. New instrumentation and upcoming facilities will propel Canadian astronomy forward to another five years of new discoveries. It is worth remembering, as much as facilities are planned to address science questions, the observational nature of astronomy leads to unanticipated discoveries that are often as revolutionary as they are surprising.

Funding for New Astronomy Facilities/Missions/personnel 2016–20

The budget presented here is an update of LRP2010 for the remaining four years of the 2010–20 decade. See Chapter 10 Discussion and summary comments for a detailed description, including its relation to LRP2010 figures and projections for 2020–25. TMT construction funding, committed in 2015, is not included. The figures given are subject to variances due to collaborative agreements and exchange rates.

	Project/Theme	2016–20 Amount
Ground	SKA Phase 1	\$60M
	Midscale innovation*	\$40M
	Sub total	\$100M
Space	Dark energy and surveys	\$100M
	CMB Polarization	\$20M
	Small payloads	\$5M
	Sub total	\$125M
People/Infrastructure	Postdoctoral funding	\$7.6M
	Laboratories	\$4M
	Total	\$236.6M
Outreach	PromoScience and NRC	\$1.2M

*Midscale innovation includes CCAT, costs for developing facilities/instruments that will have primary construction in the 2020–25 decade, including MSE and second-generation instrumentation for the TMT, and new projects that may appear. It is anticipated that these funds will come largely from existing competitive programs.

Notes of thanks and caution

On behalf of the entire Canadian astronomy community, the MTRP expresses immense thanks to the NRC, NSERC, CSA, CFI, CIFAR, and all the provincial agencies, for supporting the exceptional research that has been produced over the past five years. We also expressly thank the NRC, NSERC, ACURA and St Mary's University for providing monetary support that enabled the meetings about, writing and preparation of this report. Last, and by no means least, the MTRP is exceptionally grateful to all the members of the Canadian astronomy community who participated in the formulation of the MTRP through white papers, presentations, participation in meetings, and via email.

A cautionary note on time sensitivity: the information presented in this document is current as of February 2016. Aside from future changes to mission timelines, which can move both slower and faster, Maunakea has become a focus of concerns over future development, and TMT has recently been forced to reapply for a construction permit. The TMT situation is highly complex, and not one that the MTRP is qualified to comment on. The path forward will ultimately be determined by a resolution of the regulatory issues facing the project and, ultimately, by the will of the people of Hawaii.



2 Overview of the MTR Process

2.1 Terms of Reference

As for LRP2010, CASCA commissioned the MTR within a predetermined set of terms of reference:

I. Context

Building on the success of the original Long Range Plan (LRP), the 2010 Long Range Plan (LRP2010) made a series of recommendations to support world-leading astronomical research in Canada out to the 2020 time frame. At a time of growing international collaboration on “World Observatories”, such as the Thirty Meter Telescope (TMT) and Square Kilometre Array (SKA), many of the recommended projects are necessarily international in scope and present unique opportunities for Canada to play a role on the world stage.

While many major facilities now take a decade or more to develop, new opportunities and initiatives present themselves on a shorter time scale. Funding cycles also tend to have five-year horizons. Combined with the fact that Canadian participation has not yet been established in a number of the recommended projects, there is an important need to review the recommendations on the 2010 LRP, via a Mid-Term Review (MTR).

As for LRP2010, the MTR will be a collaborative process initiated by the Canadian Astronomical Society (CASCA) with the support of all Canadian national agencies and organizations that fund or administer astronomical research. The review will be undertaken by an Author Panel (hereafter “the panel”), led by a Chairperson. Community input will proceed via white papers, a dedicated website, the mobilization of CASCA committees, and a series of consultative town halls.

II. Statement of Task

The MTR is not anticipated to be as wide-ranging and detailed as the decadal plan outlined in the LRP2010. The key parts of the review are an assessment of the status of the LRP2010 projects, and an analysis of new opportunities. The series of priorities that result are anticipated to be relevant on a five-year timeline and are not to include major revisions or expansions of LRP2010 that are inconsistent with the original goals of the plan. The resulting review will serve as a single unified vision to reaffirm the LRP2010 process over the second-half of the 2010–20 decade.

III. Scope

Formulation of the MTR is a two-step process, namely a review followed by a prioritization exercise. It is anticipated that the MTR will address the following issues:

- 1.1. Assessment of the state of astronomy and astrophysics in Canada in the context of the priorities and goals outlined in LRP2010. A key aspect of this review is the identification of any systemic implementation gaps and hazards that have emerged in the time period since LRP2010 was released, and the risks presented to the Canadian astronomical community.
- 1.2. Identification of potential new research directions or areas of opportunity and the types of facilities and support that are needed to pursue them. This assessment will be science driven (first) and program driven (second) rather than facility oriented. This review is anticipated to primarily fill any gaps that have opened in the coverage of LRP2010. The possibilities for new facilities will be assessed separately.

- 1.3. Assessment of proposed new National and International facilities or programs, including space missions, and their relevance to the Canadian astronomical community. New facilities are on the drawing-board that were unanticipated or at least insufficiently mature during the writing of LRP2010. Development of the MTR requires that we review these facilities/missions and assess their potential impact and possible benefits to the Canadian astronomical community. Given that Canadian researchers are increasingly collaborating with international partners and many future facilities are likely to be built by international consortia, whether any distinction is drawn between National and International opportunities is at the discretion of the panel.

- 1.4. Re-affirmation of a prioritized list of facilities and programs that is essential to the success of the Canadian astronomical community. Building upon LRP2010, the list of priorities will only include those considered essential to the success of the community. This will unavoidably entail comparative and qualitative assessments, as during the review process different sub-disciplines or facilities will be compared with one another. While the decision on priorities will lie solely in the hands of the panel, it will take place following wide consultation with the community.
- 1.5. Outline of the proposed budgets. The review will also take into account that funding within the Canadian community comes from multiple agencies and ranges in size from small individual grants to large community driven projects.

IV. Approach

Projects that were approved by LRP2010 that are partly funded or underway need not be reassessed in detail. However, the impact of these facilities or programs and their relevance to astronomy and astrophysics out to 2020 should be incorporated within the MTR. Throughout the process of reviewing progress on facilities and research priorities, the panel will necessarily have to make judgments on the feasibility, technical readiness, and risks involved in supporting a particular facility or program. The panel is expected to maintain independence in this process (see X. Conflicts of Interest section), and will consult with independent authorities when necessary. It is critical to the overall success of the MTR that the assessment of science capability and budgetary demands is seen as a fair and rigorous process.

V. Selection of the Chair of the Author Panel

The selection of the Chair is a critical issue since the MTR process must be viewed to be open and without bias. A Chair that is viewed favourably by the entire community will thus bring goodwill toward the planning process. As a consequence of the sensitive nature of the choice of the Chair, the selection process will involve the Board of Directors of CASCA.

VI. Selection of the Author Panel

Once the Chair of the author panel has been appointed, the selection of the remaining panel members will begin. The additional panel members to be appointed will include a vice-Chair and between five and seven panelists. Since the panel will be required at certain points to make comparative assessments of the relative merits of different subject fields and programs, it is necessary that the panel have significant breadth in expertise. The panel

members will be selected by the CASCA President and Panel Chair, in consultation with the CASCA Board.

VII. Structure of Review: Working Groups

To provide reports to the author panel, the MTR will rely upon CASCA committees, and incorporate the community feedback provided through white papers, town hall meetings, and open discussions.

VIII. Deliverables

The author panel will deliver the final version of the MTR (in English) and associated recommendations to the President of CASCA and the CASCA Board of Directors. The MTR will then be simultaneously released, in both official languages, to the Canadian astronomical Community and all relevant parties including NSERC, the NRC, CFI, CSA, and relevant Ministries of the Government of Canada.

IX. Schedule

The review process will begin upon appointment of the Chair of the author panel, which is anticipated to be announced in January 2014. Discipline working groups are anticipated to begin their tasks as soon as they are appointed. The process is anticipated to take no longer than 18 months, with the public release of the MTR in fall 2015.

X. Conflicts of Interest

All panel members will ensure that all work conducted under their auspices is conducted in a manner free of conflicts of interest. Any persons associated with the panel are also bound to similar conduct. For the purposes of this review, a conflict of interest is defined to be a situation where any panel member or his/her family is able to benefit financially from involvement in the review process,

or if a prioritization process is perceived to benefit the individual's place of work. If a conflict of interest arises, it must be declared so that the Chair may take appropriate action. Panel members are also advised to provide early notification of the possibility of such conflicts occurring.

XI. Confidentiality

The review is expected to be an accountable and open process. Submissions to the project will be made public, although proprietary information may be so-indicated and will be kept confidential. However, prior to mutually agreed upon release dates, all panel members are to agree that they will not disclose or give to any person any information or documents relating to the MTR.

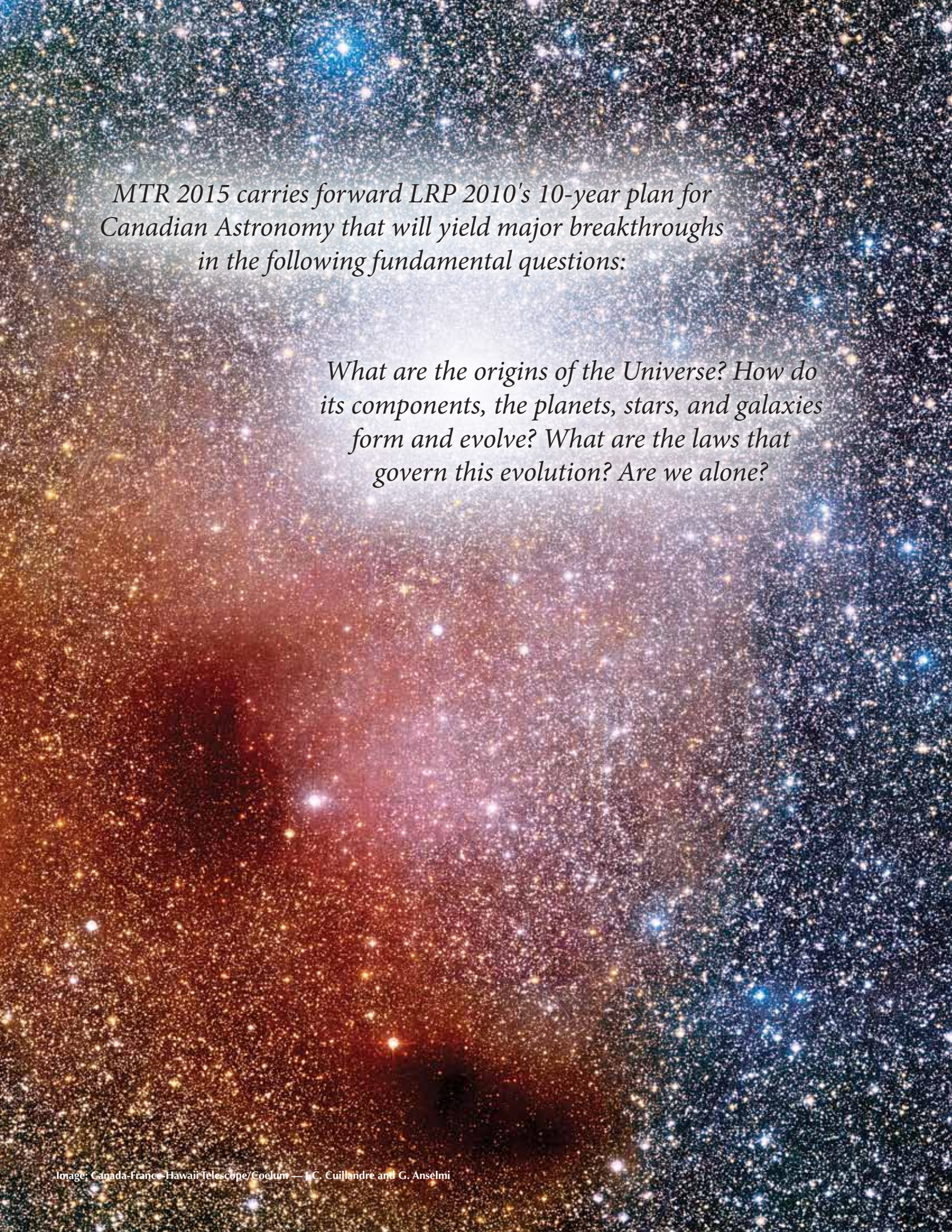
2.2 MTR process

MTR panelists were selected in the spring of 2014 through a collaborative process between the CASCA Board and the MTR Chair. The review process began at CASCA 2014, with a day devoted to discussing upcoming projects/facilities and the statuses of current ones. A call for follow-up white papers was announced in the fall of 2014, and most papers were delivered before the end of 2015. A total of 22 white papers were received by the panel, including reports from all the CASCA sub-committees. By soliciting white papers first, the review process provided ample background for CASCA members ahead of the town hall meetings. As for LRP2010, three separate and lively town hall meetings were held, in Montreal, Toronto, and Victoria on March 24, 25 and 26 respectively. The town halls were also streamed via the internet for those interested in participating remotely.

Following the town hall meetings the panel began a process of deliberation both via telecon and face to face meetings. It is worth mentioning that the funding of

TMT was announced on April 6, 2015, after the town hall meetings, but before any preliminary announcements of report recommendations. One face-to-face meeting was held in Toronto on April 20, 2015 where preliminary conclusions were discussed in detail. This served as a platform for discussions ahead of CASCA 2015 at McMaster on May 26, 2015 where preliminary conclusions were delivered to the community. Following feedback, the panel met again in July in Montreal as well as visiting the CSA two-days later to discuss space-based astronomy projects.

Detailed report writing began in the fall of 2015, with drafts of the bulk of document written by the end of November. Final collation, editing and reviewing, by a small group of senior community representatives occurred in January 2016. Community feedback was solicited following the release of the draft report in February 2016. Final typesetting and translation were completed in Spring 2016.



MTR 2015 carries forward LRP 2010's 10-year plan for Canadian Astronomy that will yield major breakthroughs in the following fundamental questions:

What are the origins of the Universe? How do its components, the planets, stars, and galaxies form and evolve? What are the laws that govern this evolution? Are we alone?

3 Science Progress 2010–15

Astronomy continues to lead the world in new, inspiring discoveries and Canadian astronomers continue to be major players in most of these, thanks to the facilities and instruments identified as priorities in previous LRPs. Progress is steadily being made on aspects of the “Big Questions” highlighted in LRP2010, but they still remain the fundamental science drivers:

1. *Where did it all come from?* The Hot Big Bang and Cosmology; the Nature of our Physical Universe; Dark Matter and Dark Energy
2. *How did it all form?* The Grand Architecture of the Universe; Formation, Evolution, and Structure of Galaxies, Stars, and Planets
3. *How does it all work?* The Laws of Physics, Extreme Physical Environments
4. *Are we alone?* Extra-Solar Planets and the Quest for Life in the Universe

The MTR panel heard that answers to these questions continue to preoccupy the Canadian astronomical community and consequently continue to drive the priorities for access to new or improved instrumentation and facilities. Virtually all of the major scientific capabilities highlighted in LRP2010 and this report e.g., TMT, SKA, MSE, WFIRST, CASTOR, etc. can be used to shed insight on aspects of all the above questions, i.e., most of these facilities are quite versatile. Furthermore, it is subsequently recognized that telescopes can be utilized in novel ways to explore areas not even contemplated during their initial design. The CHIME project provides an excellent example: initially it was designed to map the structure of neutral hydrogen in a large volume of the Universe but it is now being adapted to also investigate the origin of the as yet unexplained Fast Radio Bursts, and to study pulsars.

3.1 Are we alone?

Some of the most newsworthy discoveries of the past five years include several from ALMA, one of the new facilities highlighted in previous long range plans. ALMA is now fully constructed and beginning full science operations. The Canadian-built Band 3 receivers are performing extremely well and figure prominently in virtually all of the new discoveries. Perhaps the most noteworthy of these is the spectacular image of HL Tau (Figure 1) that demonstrates how ALMA

can probe the chemical and dynamical nature of protoplanetary disks, ultimately helping to reveal how planetary systems form. Many more results are in progress. As detailed in the ALMA section (5.1.3 ALMA), Canadian astronomers have seized the opportunity, and are making excellent use of it.

Results from the Gemini Planet Imager (GPI), an “extreme adaptive optics system,” on the Gemini South telescope are also starting to appear. Engineers and scientists at the UdeM and NRC

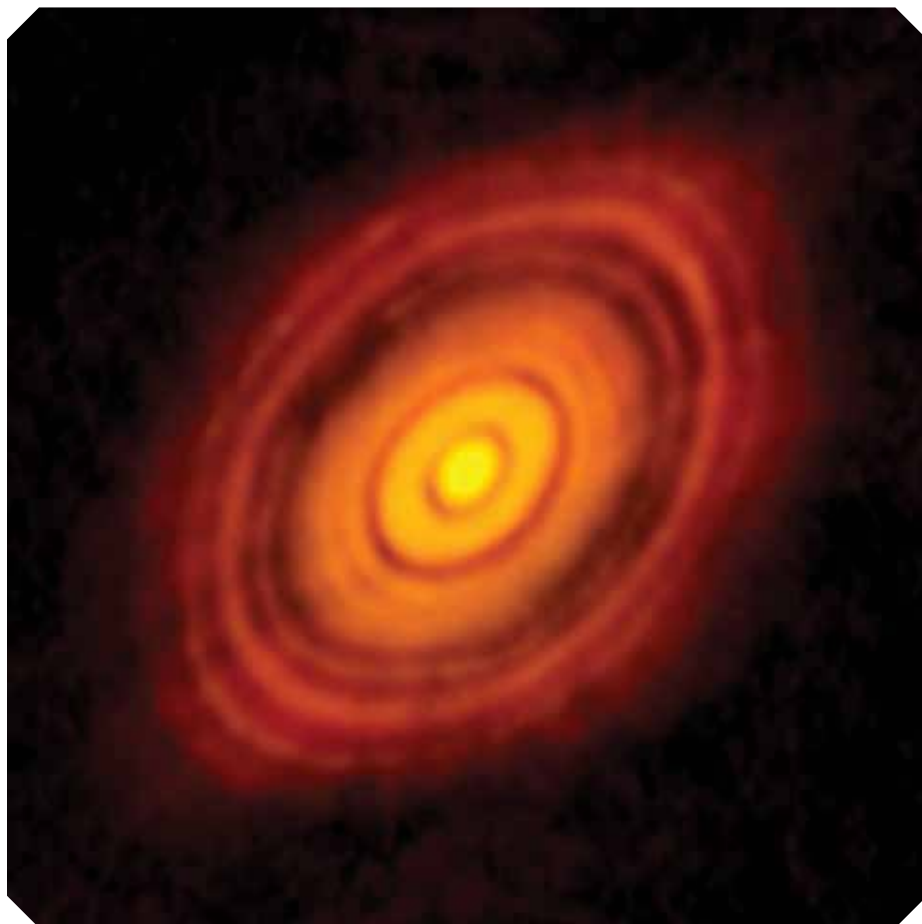


Figure 1. ALMA image of the young star HL Tau and its protoplanetary disk. This best image ever of planet formation reveals multiple rings and gaps that herald the presence of emerging planets as they sweep their orbits clear of gas and dust. Credit: ALMA (NRAO/ESO/NAO); C. Brogan, B. Saxton (NRAO/AUI/NSF)

Herzberg played very major roles in this instrument and Canadian scientists are already reaping the rewards. One of the most exciting discoveries so far is a planet that appears to be very similar to Jupiter orbiting the star 51 Eridani about 100 ly away. Stellar age estimates suggest that 51 Eridani is only around 20 million years old; making this is a young planetary system that can help shed light on planet formation processes. Theoretical models suggest the gas in giant planets can be accreted in ways that lead to a “hot start,” in which gravitational energy is trapped making the infant planet hot, or a “cold start” in which accreting gas is shock heated allowing it to radiate away a lot of the energy. Almost all observations to this point had been too bright to be considered cold start candidates. Intriguingly, the planet, denoted 51 Eridani b, has the strongest methane signature of any extrasolar planet and is also of sufficiently low luminosity to possibly be a cold start candidate. The observed luminosity suggests the mass of the planet is between two to twelve Jupiter masses in cold start scenarios. Alternatively, if a hot start is assumed, the mass is around two Jupiter masses. The discovery garnered a lot of attention in the press² and was outlined in an important article in *Science* magazine.

These are precisely the type of results that were hoped for when the GPI project was initiated.

Canadian astronomers also used the GPI and Keck telescopes to study the chemical composition and atmospheric structure of two of the planets surrounding HR 8799, one of the discoveries highlighted in LRP2010. The ability to perform detailed studies of other extra-solar planets like

those around HR 8799 and protoplanetary disks like HL Tau is certain to be transformative in our understanding of the origin and evolution of planetary systems and, indeed of earth-like planets. Observations with ALMA, JWST and TMT will be of paramount importance in this quest. As an example of the synergy, ALMA can study the outer, colder regions of protoplanetary disks while TMT will provide a direct look at the inner (less than a few astronomical units), warmer regions where terrestrial and giant planets form. ALMA will also reveal the tidal gaps created by protoplanets, and TMT will image these protoplanets themselves through high-contrast imaging. In the mid-infrared (MIR) the sensitivity of TMT/MIRES to an un-resolved spectral line is comparable to JWST/MIRI but with spectral resolution sufficient to understand the underlying physics. Spectra of gaseous lines with TMT will provide critical velocity information to understand the radial location of the gas, and how the dynamical/chemical/physical structure of these disks will evolve with time.

It isn't surprising that these areas of research are amongst the fastest growing areas of astronomy, and Canada is playing in leading role in their development.

3.2 How does it all work?

Canadian astronomers at the universities of McGill, Toronto and British Columbia, were part of an international team that discovered and carried out extensive observations of an extremely high mass (twice the mass of the Sun) pulsar in a very compact orbit around a white dwarf.

This system provides a sensitive laboratory of a previously untested strong-field gravity regime. Thus far, the observed orbital decay agrees well with the predictions of Einstein's Theory of General Relativity (GR), supporting its validity even for the extreme conditions present in the system. Since many physically motivated extensions to GR predict significant deviations in the properties of spacetime surrounding massive neutron stars these results are very significant – and will continue to be improved through ongoing observations of this unique system.

The discovery that neutrinos can change identities and have mass is a huge step forward that has major impacts for both fundamental physics and the evolution of structure within the universe. On October 6, 2015, the Nobel Prize committee awarded³ the 2015 Physics prize jointly to T. Kajita of Japan and Arthur B. McDonald of Queen's University, Canada. Observations at the Sudbury Neutrino Observatory (SNO) were central to the determination of the properties of neutrinos, a facility that was largely created by funding from NRC and NSERC almost three decades ago⁴ and SNO has enjoyed NSERC support for the university-led collaboration ever since. As the press release states “the discovery has changed our understanding of the innermost workings of matter and can prove crucial to our view of the universe.” On November 8, 2015, it was further announced that Arthur McDonald and the SNO group shared in the 2015 Breakthrough Prize for Fundamental Physics. These prizes are the highest recognitions of the roles that Canadians play in trying to solve the mysteries of the Universe. These give a tremendous boost to our science.

2 And a nice semi-popular article in Scientific American (<http://www.scientificamerican.com/article/astronomers-glimpse-a-young-jupiter-51-eridani-b/>)

3 http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/press.html

4 There are many parallels between the ways the funding for SNO and TMT were achieved (for SNO, see Ewan, G.T. and Davidson, W.F, Physics in Canada, Nov/Dec 2005). It appears that the process for funding big science hasn't basically changed over the past three decades, except that NRC and NSERC were able to actively lobby for government support before SNO was eventually funded in 1990.

3.3 Where did it all come from?

Canadians were important participants in the Planck and Herschel satellites that were launched in 2009. Both of these missions were outstandingly successful and the results, particularly in cosmology through CMB studies, continue to rank among the highest impact areas in astrophysics in Canada. Canadians from both academia and industry played key roles in several areas, including hardware, theory, algorithms, experience and expertise. The results still pouring out of Planck and Herschel demonstrate that the \$21M contributed by Canada through CSA was exceedingly well spent.

As detailed in the CMB satellite section

(6.3 Cosmic Microwave Background Polarization Missions), we can now also begin to look forward to results derived from precision measurements of CMB polarization from both balloons and satellites to unlock new cosmological information and qualitatively new science. The MTR panel was impressed to learn that the unique Canadian technology and expertise in CMB studies will continue to provide important clues toward solving some of the deepest problems in modern physics: the nature of dark matter, dark energy, and the physics responsible for generating the initial fluctuations.

In 2011 the Supernova Legacy Survey (SNLS) team published the results of a huge imaging survey with CFHT designed to detect distant supernovae, followed up with spectroscopy from Gemini, VLT and

Keck telescopes. When combined with results from WMAP and other projects, the precision to which several of the fundamental parameters of the universe can be constrained is truly remarkable: the matter density of the universe to within 5%, the dark energy equation of state parameter, which measures the ratio of the energy's pressure to density, to within 6.5%. It is worth bearing in mind that just two decades ago these numbers were not even known to within factors of two!

3.4 How did it all form?

The results of another major survey with CFHT, the Pan-Andromeda Archaeological Survey (PAndAS), revealed a substantial population of dwarf satellite galaxies

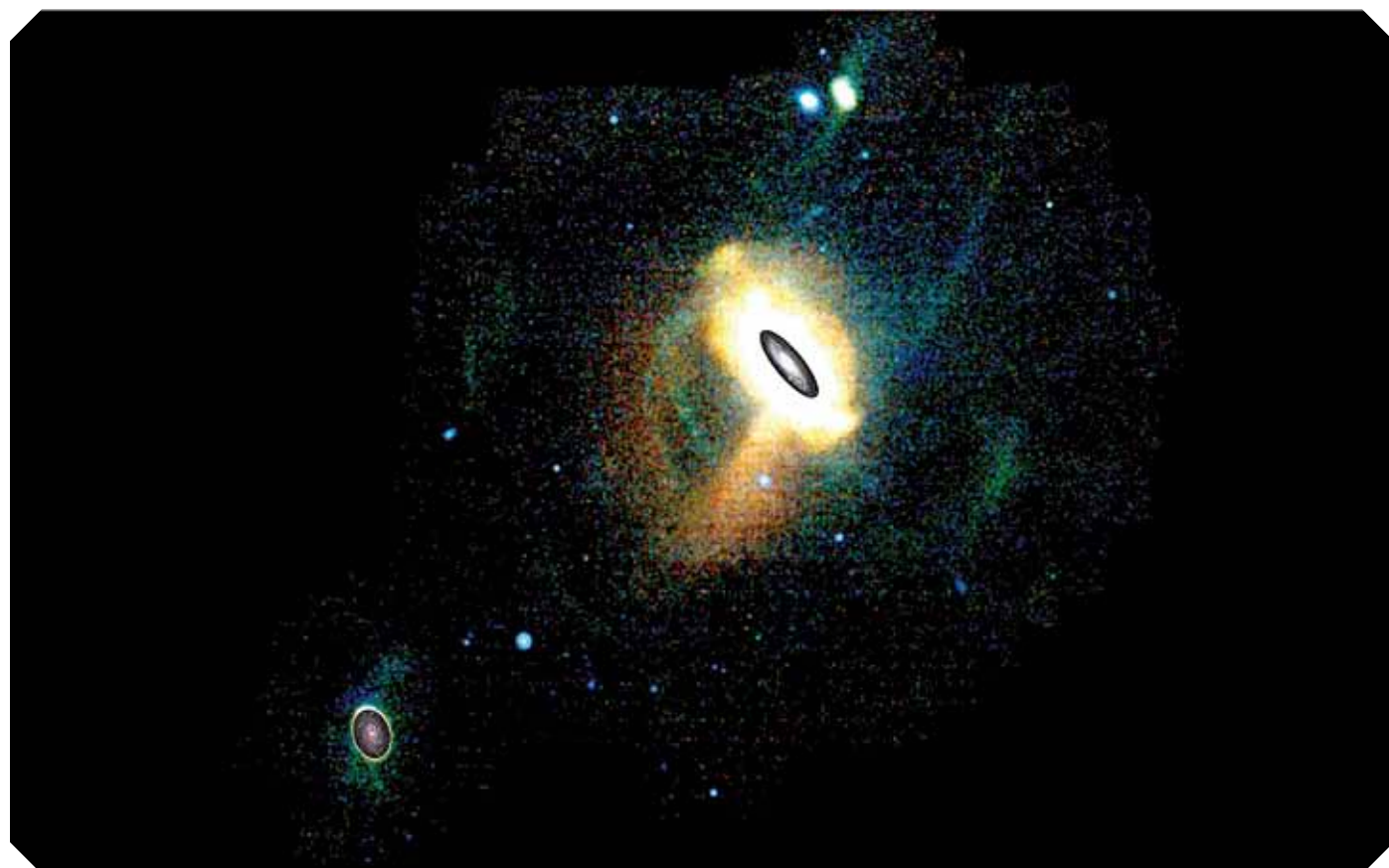


Figure 2 The Andromeda galaxy environs imaged, in three separate colours, as part of the PAndAS survey. Structures down to exceptionally faint magnitudes extended out much further out than the disk (shown as an insert).

around M31 as well as streams of stars that are obviously the results of interactions with such galaxies in the past. Figure 2 shows one of the results from the PAndAS survey, in which the blue, green, and red channels correspond to signal stellar populations with progressively higher proportions of metallic elements. The apparently tiny images of M31 and M33 that are inset demonstrate the huge dimensions of the streams. A *Nature* paper in 2013 detailed results showing, highly unexpectedly, that the dwarf satellites are located in a remarkably thin co-rotating plane. Surveys like this one of other nearby galaxies have the potential to reveal how galaxies form from dark

matter halos, especially when combined with kinematic and age determinations from massive spectroscopic surveys like those planned for MSE.

Among numerous results by Canadians with ALMA on the more distant universe, the discovery that many of the highly obscured sources are actually gravitationally lensed galaxies at high redshift stands out as illustrative of the tremendous gains brought by the improved sensitivity and spatial resolution of ALMA. As mentioned above, TMT will also bring similar improvements in spatial resolution and sensitivity and will have the same spatial resolution as ALMA in the NIR.

3.5 Summary

During the past five years Canadian astronomers continue to excel in the very competitive international environment thanks to the facilities and support embodied in LRP2010. Panel members were truly impressed by all the new exciting results discussed during the MTR process and were encouraged by the progress that has occurred since 2010. The announcement that Canada will become a full partner in TMT is a huge step forward in achieving the aspirations of Canadian astronomers.

4 Astronomy and Society

4.1 Astronomy and Canada's Strategic Plan for Science and Technology

LRP2010 highlighted the importance of Astronomy in the foundation of Canada's innovation and technology strategy. In the past five years significant further analysis of this sector has been undertaken.

On November 27, 2015, the Science, Technology and Innovation Council (STIC) released a detailed report entitled, *"State of the Nation 2014,⁵ Canada's Science, Technology and Innovation System."* The opening executive summary paragraph emphasizes that, *"A sustainable competitive advantage in ST&I is the path to success in the global knowledge-based economy"* and its primary five recommendations contain within them a *"boost [to] higher education expenditures on R&D to keep pace with other countries"*. The report focuses on a systems approach, wherein the responsibility to improve Canada's relatively poor business innovation performance must be addressed by improving three pillars:

- i) skilled and creative talent
- ii) high-quality knowledge
- iii) an innovative private sector.

Indeed, astronomy and its related technology development address all three of these innovation pillars: i) and ii) are addressed directly, while iii) is addressed through university/NRC/CSA partnerships, whose contracts with industry produce state of the art instruments for astronomy. The technology and skill sets transferred to industry are re-used in related fields such as national defense, information technology and medical imaging.

University- and NRC-based technology development teams in astronomy are addressing the most important pillar that fuels innovation in the private sector. Investment in new astronomical facilities spurs the creation of new technologies, particularly in optical science, high speed data networking, remote sensing, space technology, and large-scale computation. This has been confirmed in independent analysis. The 2014 Doyletech Report on astronomy technologies, commissioned by the NRC, highlighted six key technologies from the TMT and SKA projects that provide initial entry into markets estimated to have a total value of several hundred billion dollars, and which are also anticipated to grow by around 8% per year. While these numbers are clearly estimates, the report echoed *"It's hard to translate into dollars the opportunity enhancement in the NRC-industry-university ecosystem."*

Astronomy's broad popularity has also led to the public becoming directly involved in scientific discovery through the process of Citizen Science such as SETI@home and Galaxy Zoo. While moderately rare at present, important discoveries have been made by citizens, the standout example being "Hanny's Voorwerp" an exceptionally rare configuration of gas ionization related to an active galactic nucleus that provides detailed constraints on changes in galactic nucleus luminosities. With well over twenty projects online as well as possibilities for backyard discoveries of comets, new phenomena in variable stars or low surface brightness features, astronomy offers unparalleled opportunities for accessible hands-on training that leads to real discoveries.

Following the election of a new Canadian government on October 19, 2015, astronomy now falls broadly under the

mandate of the newly created Department of Innovation, Science and Economic Development (ISED). The MTRP applauds the recognition given to the importance of science to policy decisions, and as a national investment. A number of the top priorities in both the mandates of the Minister of ISED,⁶ the Hon. Mr. Navdeep Bains, and the Minister of Science,⁷ the Hon. Dr. Kirsty Duncan, are directly impacted by, or have relevance to, astronomy.

Specifically, for the Minister of ISED, two key priorities of relevance to astronomy are:

"Expanding effective support for incubators, accelerators, the emerging national network for business innovation and cluster support, and the Industrial Research Assistance Program. These investments will target key growth sectors where Canada has the ability to attract investment or grow export-oriented companies. You will assist the Minister of Finance to ensure tax measures are efficient and encourage innovation, trade and the growth of Canadian businesses; and working with Regional Development Agencies to make strategic investments that build on competitive regional advantages. For those communities that have relied heavily on one sector in the past for economic opportunities, investments that support transition and diversification may be appropriate. Communities that have relied on traditional manufacturing are likely to require specific strategies to support economic growth."

⁵ <http://www.stic-csti.ca/eic/site/stic-csti.nsf/eng/home>

⁶ <http://pm.gc.ca/eng/minister-innovation-science-and-economic-development-mandate-letter>

⁷ <http://pm.gc.ca/eng/minister-science-mandate-letter>

As discussed in Section 4.2 Industry and Economic Impacts, over 200 Canadian companies are or have been involved in the development and construction of astronomy technologies and facilities. Many of these companies are smaller start-ups that evolve out of technological developments in astronomy that exhibit entrepreneurial potential. The majority of these innovations open up new application markets and present strong growth opportunities. At the same time, astronomy research has a broad base across the country, and entrepreneurial developments happen across Canada.

For the Minister of Science, one of whose stated goals is “to support scientific research and the integration of scientific considerations in our investment and policy choices,” three key priorities of relevance to astronomy are:

“Create a Chief Science Officer mandated to ensure that government science is fully available to the public, that scientists are able to speak freely about their work, and that scientific analyses are considered when the government makes decisions.

Support the Minister of Employment, Workforce Development and Labour in efforts to help employers create more co-op placements for students in science, technology, engineering, mathematics, and business programs.

Examine options to strengthen the recognition of, and support for, fundamental research to support new discoveries.”

The MTRP applauds the creation of a Chief Science Officer as an important component of science policy in Canada. In terms of student opportunities, astronomy has a significant history of summer studentships and industrial placements. Additionally,

many of these placements offer significant “cross-fertilization” potential between science and engineering, giving students a wider perspective on future careers, as well as exposing them to a collaborative working environment where knowledge is broadly shared. With respect to examining options in support of fundamental research, the MTRP emphasizes that the LRP planning mechanism is a key strategy for maximizing astronomy research quality in Canada. At the same time, the LRP process considers both national and international research landscapes, as well as innovation and technological issues.

Astronomy fits well within the last science and technology strategy to be released by the Government, as outlined in the “Mobilizing Science and Technology to Canada’s Advantage” document, which presented four central themes:

1. Promoting world-class excellence: In the international arena, Canadian astronomy and space science has the highest impact of any of the sciences. *Physics and Astronomy* is listed by the Council of Canadian Academies as one of the six research fields where Canada excels. Canadian astronomy ranks highest in impact of any country in the G8.
2. Focussing on priorities: a few examples showing how astronomy is related to each of the previously listed S&T priorities are given below. These are a subset of the many existing examples.

Natural resources and energy: Astronomy relies almost entirely on obtaining information through remote sensing. Image analysis techniques developed by astronomers are routinely used to interpret images of Earth taken from space. Most images obtained by remote sensing satellites are taken using Charge-Coupled Devices (CCDs), whose early development was also driven by astronomers.

Health and related life sciences and technologies: Astrophysical research has found applications throughout medical imaging. Techniques originally developed for radio astronomy are used in tomographic reconstruction of the human body in CAT and PET scans. LASIK eye surgery uses techniques originally developed for adaptive optics on telescopes, a Canadian research specialty. Astronomical instrument makers played a key role in developing keyhole cameras for laparoscopic surgery. Medical X-ray imaging uses techniques developed for astronomical X-ray imaging.

Information and communications technologies: The basis for Wi-Fi networking technology originates in radio astronomy. By 2014 the world market for Wi-Fi appliances will likely be in excess of \$250 billion. A 1977 paper, co-authored by Dr John O’Sullivan, describes techniques to help improve images from radio telescopes. Almost twenty years later O’Sullivan applied the results of this earlier work to reduce interference of radio signals used to carry computer networking and this gave rise to a substantial part of the 802.11 standard. This example also shows how astronomy personnel can drive innovation in the private sector.

Environmental science and technologies: Astrophysical research also informs the technology used in environmental sciences. Many of the technological innovations behind Canada’s instruments on JWST trace their origin to Canadian contributions to the WINDII (Wind Doppler Imaging Interferometer) aboard the American UARS (Upper Atmosphere Research Satellite). At the same time, some of the satellite-pointing technology in Canada’s RADARSAT series of satellites can be traced to Canadian contributions to the pointing system on NASA’s Far-Ultraviolet Survey Explorer, or FUSE.

3. Encouraging partnerships: Astronomy is one of the most collaborative sciences, with large facilities shared between many nations and built through large-scale collaborations between governments/universities and local industry. Indeed, the vast majority of infrastructure funding for astronomy flows to Canadian industrial partners that are often engaged in delivering hardware that pushes the boundaries of their capabilities and makes them more competitive for future ventures.
4. Enhancing accountability: The accountability of astronomy to society is managed primarily through our work in education and public outreach, discussed in Section 4.4 Education and Public Outreach.

In summary, astronomy research contributes directly to the themes that have been identified by numerous reports as foundational to our nation's systems-strategy for addressing Canada's innovation gap.

4.2 Industry and Economic Impacts

More than 200 Canadian companies⁸ are or have been involved in developing, fabricating and/or commissioning components for Canadian astronomy facilities or instruments on the ground or in space.

Most of these involve innovative or frontier techniques, driven by the desire to gain better and deeper insight into the origin and physics of our Universe. The interactions and relationships among all the players, industries, NRC, CSA, university physics, astronomy and engineering departments, etc., has been steadily growing and improving as interests align more closely and instruments become larger and more complex. The MTR panel was encouraged to hear that there are ongoing efforts to strengthen these links and that there is a mutual desire to develop and improve, for example, technology transfer methods, intelligent procurement strategies and, in general, to forge closer links and improve dialogue. In most cases, the investments in the projects identified as priorities for astrophysics in the LRP are equally investments in the abilities and competencies of Canadian industries.

The HAL report emphasizes the socio-economic impact of Canadian astronomy in five key areas:

Knowledge generation

Knowledge use

Development of HQP

Contribution to Partnerships

Contribution to Innovation

The report calls out the particularly important role of Astronomy innovation in Canada:

"The impact of astronomy research on technology advancement comes not from the astronomy research per se but rather from the pioneering instruments that astronomers have developed to conduct their ever more ambitious research. With each new telescope, scientists and engineers have pushed the technological frontiers in sensor design and spatial resolution, allowing for major improvements..."

Innovation, and the training of HQP to initiate and advance innovative technologies, has been identified as crucial to the Canadian economy and an area where we fall behind other G8 partners. The 2015 STIC report, previously mentioned, concluded that Canada's poor business innovation performance represents the country's most profound and urgent challenge in science, technology and innovation. They noted that whereas in terms of knowledge "Canada enjoys some real 'star power' in the scientific world," this is not translated to innovation in business.

Our experience is that astronomy plays an important role in attracting, inspiring, and training our future engineers and entrepreneurs. The opportunity to work on awe inspiring projects like JWST, TMT, SKA, etc. is exceedingly attractive, and is excellent resume building material. Importantly, these vast public projects are not subject to secrecy like competitive industrial or military projects, and foster open discussion and collaboration between students in the science and engineering communities. This sense of collaboration is further supported by the international astronomy community's tra-

Technology development for astronomical instruments is a key innovation driver in Canada and comes at effectively no net cost to Canada. According to the Hickling, Arthurs, Low (HAL) report on Canadian astronomy, "the expenses incurred by the Canadian government for these two observatories [Gemini, ALMA] are approximately equal to the quantifiable economic impacts for the country, which are in addition to the notable unquantifiable social benefits described above."

⁸ Coalition for Canadian Astronomy figures.

dition of openly sharing information and techniques. Thus researchers and students are exposed to the latest innovations worldwide and are able to build on those to develop ever more capable instruments and techniques.

The HAL report also investigated the economic impact of two recent major astronomy projects (Gemini, ALMA) in some detail and concluded:

“Overall, therefore, the expenses incurred by the Canadian government for these two observatories are approximately equal to the quantifiable economic impacts for the country, which are in addition to the notable unquantifiable social benefits described above.”

A report to NRC in 2013 by ACURA entitled “The Thirty Meter Telescope and Astronomy in Canada” provides further details and testimonials on direct benefits to society in non-academic careers by astronomy graduate students, and illustrates which areas benefit most (industry, teaching, computing and finance). According to this study, about 1/5 of PhD graduates entered employment via a combined industry/non-PSE-teaching/government channel and about 1/3 of these transitioned directly to industrial positions. Teaching accounted for a further 1/4 of this category, finance, and general software development another 1/4, with the remaining occupations being government and medical careers. We note, however, that this analysis refers to science students and does not include all the engineering and technical students that are increasingly becoming involved in sophisticated forefront instrumentation. For example, 151 of the 211 students (predominantly co-op students) that

worked in NRC astronomy labs during 2003–9 were non-science students, i.e., they were mostly in engineering and computing. Anecdotally, many of these students end up in positions in industries in Canada, although no good national data are available to our knowledge.

Most Canadian space astronomy facilities and instruments are fabricated by aerospace companies but now instruments for large ground-based facilities are increasingly being led by professional engineering teams in industry and national labs, with the involvement of professors and students in both astronomy and engineering. Astronomy projects very often push technology to the limits. For example, extremely low noise amplifiers in the 4 – 8 GHz range were required to meet the system level goals of the ALMA Band 3 receiver project. Such a low noise temperature, < 3.5 K at 12 K ambient temperature, over such a wide frequency range had never before been achieved. More than 70 of these were required for ALMA. Engineers and technicians from Nanowave Technologies of Etobicoke ON worked closely with NRC engineers to learn how to transform prototypes into state-of-the-art industrial components. Nanowave has subsequently supplied copies of these amplifiers for other projects (e.g., the MeerKAT SKA precursor), and these components are now listed as one of their advanced products on their website.⁹

As described in LRP2010, Dynamic Structures Limited of Port Coquitlam, BC, built upon their initial success designing, fabricating, and installing the enclosure for CFHT on Maunakea to become “the premier provider of dynamic, complex structures utilized for industry, government, academia, and entertainment” in the world.¹⁰ They will provide the massive enclosure for TMT, a novel design that delivers exceptional perfor-

mance in an efficient structure – and that has already become an icon.¹¹

It is anticipated that there will be significant industry involvement in the instrumentation for major facilities like TMT, ALMA, and SKA, not solely in the construction of the facilities themselves, but leading to significant potential commercialization. The 2014 Doyletech study of technologies being developed at NRC Herzberg is strongly supportive of this conclusion. This analysis considered six key technology developments and assessed the overall size of the markets associated with the technology. The study estimates obtained were:

Adaptive optics technologies:
\$325B market

Precision probe positioning:
\$40B market

Phased array feeds: very new —
awaiting direct applications

Cryogenic Low noise amplifiers:
\$56B market

Aperture array digital signal processing: \$8B market

Composite reflector antennas:
\$4B market

While these markets are obviously global estimates across all applications, it is clear that the potential for impact is large. In addition, these studies have not considered the impact of data analytics developed in astronomy. The overall market value for “Big Data” is now estimated to be \$125B by International Data Corporation and average spending in this sector is anticipated to grow at 20% per year in the next five years.

⁹ <http://nanowave-technologies.blogspot.ca/>

¹⁰ <http://www.empind.com/portfolio/dynamic-structures-ltd/engineered-products>

¹¹ <http://www.empind.com/portfolio/thirty-meter-telescope-tmt/new-designs>

Thus public investment in astronomy has the potential to create significant opportunity, and value in markets that are already large. Combined with the societal benefits inherent in discovery and knowledge transfer, the overall value proposition for investment in Canadian astronomy is extremely high.

Evolution in the education and skills discussion

While the LRP process has traditionally not discussed specifics of educational programs, one significant change in the last five years has been the growing commentary on vocational aspects of educational programs, at the bachelors through to PhD level. Much of this discussion is in the context of concerns about the uncertain nature of future employment and job supply, and the increasing numbers of students in post-secondary education.

Graduates of astronomy programs naturally develop key parts of the “Employability Skills 2000+” list, a commonly cited table of skills developed by the Conference Board of Canada. The first category, the “Fundamental” skill set, covering communication through to problem solving, are implicitly needed for success in the research environment. The second skill set of “Personal Management” is related to attitude, handling of responsibility, ability to adapt and continuously learn. While attitude is difficult to teach in any specific sense, responsibility is a natural part of completing a degree as are adaptation and learning. The final “Teamwork” skill set focuses on working and relating to others, as well as the ability to plan and participate in projects. Astronomy projects are increasingly collaborative, meaning that many students are quite naturally exposed to teamwork and students are often actively involved in outreach. However, while it is common for students to undertake research as part of a larger project or collaboration, it has been noted that

comparatively few students receive formal training in project management.

Feedback from science graduates that have transitioned to industry (see the Naturejobs¹² website for excellent commentary), has been positive on value of skills learned during degrees. The follow-up survey on astronomy entrepreneurs conducted by ACURA as part of a report on TMT for the NRC produced a universal chorus of agreement that many of the skills they learnt during their degree served them well in industry. Commentary from individuals that have transitioned into data science has also been useful, both in highlighting the value of interpersonal skills, but also the value of statistical and database techniques and “standards.” Specifically, graduates able to use common programming and query languages in industry, e.g. Python, R, and SQL had a significant advantage during interviews for industrial positions.

Thus, while the central focus of teaching in astronomy should always be the provision of skills for astronomy, and departments must set their own agendas, there is clearly potential for small changes to graduate training that can benefit both the academic- and industry-track careers. Collected testimony suggests that careful thought should be given to including the following three factors/domains:

Project management skills

Statistical methodologies and machine learning

Transitioning to common programming/query languages in the teaching sphere

A last testament to the value of these skills is that some graduate students are already taking it upon themselves to develop them via independent study.

4.3 Institutes and Laboratories

A variety of Canadian institutes and laboratories enable the ground-breaking research on which the astronomical community’s international reputation for excellence was built. This section highlights these facilities, focusing on new developments since LRP2010.

NRC Herzberg

NRC Herzberg Astronomy and Astrophysics (NRC Herzberg), formerly the Herzberg Institute for Astrophysics (HIA), is unique within NRC in its focus on enabling the advancement of astronomy in Canada. As Canada’s de facto national astronomy laboratory, its activities are critical to the success of the Canadian astronomical community on the world stage.

NRC Herzberg has a mandate to administer astronomical facilities on behalf of the Government of Canada. Fulfilment of this obligation is undertaken through three distinct research programs; astronomy technology (AT), optical astronomy (OA) and radio astronomy (RA). Within these three programs, NRC Herzberg operates Canada’s national observatories, the Canadian Astronomy Data Centre, and carries out major instrumentation research projects in collaboration with industry and universities.

NRC Herzberg establishes its research priorities primarily from the LRP, as well as through consultation with the astronomical community by way of organizations such as ACURA. As such, a significant fraction of NRC Herzberg’s activities since LRP2010 have focused on supporting TMT and SKA, for example through the design and development of the NFIRAOS instrument (see Section 5.1.1 TMT) and the SKA1-Mid correlator/beamformer (see Section 5.1.2 SKA). Base budget funding to NRC Herzberg in order to carry out

¹² <http://www.nature.com/naturejobs/science/>

these activities has been effectively constant since LRP2010, now averaging about \$17.4M per annum excluding salaries.

However, the re-organization that saw HIA transition to NRC Herzberg on April 1, 2012, has raised serious governance issues that threaten NRC Herzberg's ability to support the astronomical community consistently with its mandate. The MTRP sees these governance issues as a fundamental challenge for NRC Herzberg and the Canadian astronomical community moving forward; a detailed discussion of these issues can be found in Chapter 8 Governance, Funding and Budgets.

University-based Laboratories and Principal Investigator Telescopes

Some of Canada's most innovative instrumentation projects and important training work is carried out in university-based laboratories. As highlighted in LRP2010, at least 10 universities across the country host active instrumentation groups, which design tools and techniques for astronomical facilities across the electromagnetic spectrum. The majority of these groups are relatively small in size, consisting of faculty, technical staff, PhDs, and students. They are nonetheless highly productive, designing, developing and manufacturing instruments and components for some of the world's most ambitious ground- and space-based projects. Indeed, the majority of Canadian astronomy instrumentation projects over the last decade can trace their origins back to intellectual developments that arose out of university-based laboratory research.

Most university-based laboratories rely on a combination of federal (e.g. CFI, CSA, and NSERC) and provincial (e.g. FQRNT) programs to fund their activities. By necessity, most of these groups maintain their vibrant, long-term programs by stringing together a series of short-term grants. In this context, the loss of the Special Research Opportunity

program at NSERC was a particularly challenging blow to the funding of laboratory-based projects. However, LRP2010 also noted the inherent difficulty of maintaining a stable core of expertise with this short-term approach, and advocated for the creation of a renewable funding program by NSERC and the CSA.

Looking to the future, second-generation instrumentation projects for TMT will tax the ingenuity of instrumentation laboratories and if underfunded this will further hamper prospects for Canadian leadership. At the same time, it is worth noting that many of the technological spin-off companies associated with astronomy arise out of the commercialization of laboratory developments.

Taken together, all these factors compel the MTRP to reiterate the concerns expressed in great detail LRP2010. A stable funding flow to university-based experimental astrophysics laboratories, from both federal and provincial agencies, is an absolute requirement for successful participation leading-edge astronomical facilities.

Recommendation: *The MTRP strongly reaffirms the need for stable funding of university-based astrophysics laboratories, both as a generator of new instrumentation ideas as well as an important complement to the larger laboratory infrastructure present at NRC Herzberg.*

Canada's smaller facilities provide critical testbeds for prototyping new instruments and techniques developed in university-based laboratories, as well as providing key scientific observations that support major initiatives on the world's largest facilities. HIA operates 1.2 m and 1.8 m optical telescopes at the Dominion Astro-

physical Observatory (DAO), as well as a suite of small radio telescopes at the Dominion Radio Astrophysical Observatory (DRAO). Oversubscription rates for these facilities have remained unchanged since LRP2010. They are also popular destinations for visitors interested in astronomy, although the closure of the Centre of the Universe has stunted education and public outreach efforts at DAO (see Section 4.4 Education and Public Outreach).

L'Observatoire du Mont Mégantic (OMM), jointly operated by U. Laval and U. de Montréal, is Canada's only university-based research telescope. Over-subscription rates for OMM are quoted as 1.6 and are essentially unchanged from LRP2010, and the telescope remains an important platform for instrument development through the LAE. In addition, the Astrolab visitor centre in the Mont Mégantic provincial park attracts tens of thousands of visitors per year. LRP2010 recommended continued financial support for the operation of Canada's small telescopes, but funding for OMM has been extremely uncertain, with several threats of closure. Operations are currently supported by a federal government grant following the latest crisis in early 2015; more financial stability is clearly needed.

Recommendation: *The MTRP re-iterates the need for continued funding of productive Canadian small telescopes.*

Since its inception in 2010, the Dunlap Institute for Astronomy and Astrophysics (hereafter, Dunlap) has grown into a dynamic facility at the University of Toronto. Its mission is to develop innovative astronomical technologies, to train the next generation of astronomers, and to foster public engagement in science. Dunlap currently employs five faculty members and 13 postdoctoral fellows, eight among the latter holding prestigious Dunlap Fellowships that are awarded annually following an open competition. Dunlap personnel collaborate closely with the University of

Toronto's Astronomy and Astrophysics Department as well as with the Canadian Institute for Theoretical Astrophysics (CITA), and six faculty members and 18 graduate students from these organizations are formally associated with Dunlap.

A clear boon for the University of Toronto, Dunlap has also had a positive impact on the Canadian astronomical community as a whole. Most notably for researchers, Dunlap has brokered a partnership between the University of Toronto and the LSST Consortium to provide LSST access to 10 Canadian faculty and their junior researchers at a level equivalent to that of US and Chilean scientists (see Section 5.2.6 LSST). Dunlap will absorb half the cost of those memberships, and will manage the newly created Canadian LSST Consortium responsible for selecting the 10 faculty and exploring options for expanding LSST access to include a larger Canadian community. Dunlap also established CASCAs Dunlap Award for Innovation in Astronomical Research Tools in 2013, which recognizes outstanding Canadian contributions to the design, invention, or improvement of instrumentation or software.

Pedagogically, Dunlap has partnered with the University of Toronto's Astronomy and Astrophysics Department and CITA to provide summer undergraduate as well as graduate research opportunities. Dunlap also runs a successful summer school to introduce upper year undergraduates to astronomical instrumentation, attracting participants from Canada and around the world. It has also played a key role in streamlining the outreach efforts by University of Toronto astronomers by launching a redesigned outreach website in 2014.

Theoretical Astrophysics

Canada hosts two internationally recognized powerhouses in theoretical astrophysics: the publicly funded Canadian Institute for Theoretical Astrophysics (CITA), and the Perimeter Institute (hereafter,

Perimeter), which is funded by a combination of private and public contributions.

A world-class, high-visibility institute, CITA comprises seven faculty and 25 post-doctoral fellows who carry out research on a variety of topics in theoretical astrophysics ranging from compact objects to the early universe. Co-located with the University of Toronto's Astronomy and Astrophysics Department as well as with Dunlap, CITA enjoys close collaborations with these institutions in research, training and outreach initiatives. In recent years, CITA has also developed important collaborations with major observational facilities including Planck, CHIME (see Section 5.2.4 CHIME), pulsar VLBI, LIGO and CCAT (see Section 5.2.5 Single-dish submillimetre facilities). The CITA National Fellow PDF program remains an important link between CITA and the broader Canadian community as well as a cost-effective, long-term source of theoretical astrophysics expertise across the country. Despite the need for theoretical research growing in-step with the commissioning of new facilities and instruments, the launch of JWST in 2018 stands out as a highly significant issue in this regard, funding levels for the National Fellow program through the NSERC grant have remained unchanged since LRP 2010. Given the shared nature of costs in the National Fellows program, and its potential to leverage other funding sources, the MTRP thus re-iterates the LRP2010 recommendation for an increase in CITA's NSERC support in order to expand this program.

Recommendation: *The MTRP reaffirms the value of increasing NSERC's support to CITA to augment the National Fellows program, which has proven exceptionally successful in attracting talented post-doctoral researchers to Canada, with four additional positions.*

Perimeter has grown substantially since LRP 2010, and now comprises 25 faculty and over 60 postdocs across nine disciplines in foundational theoretical physics. It has built considerable expertise in cosmology, with a total of 10 faculty and associated faculty specializing in this area. Perimeter engages with the broader community through a broad range of opportunities for researchers, students, teachers, and the public, both through its own programming as well as through partnerships with a variety of institutions in Canada and abroad. Notably, Perimeter Scholars International (PSI) has just graduated its fifth class of 30 students. This course in theoretical physics brings the best and brightest international talent to Perimeter for an intense 10-month program while earning an MSc from the University of Waterloo. Over a third of the 2014 PSI class has remained in Canada to pursue PhD studies: PSI therefore provides an important new mechanism for bringing theoretical physics talent to Canada.

4.4 Education and Public Outreach

LRP2010 was authored a year after the International Year of Astronomy, which was viewed by all as a resounding success. Although the report made specific recommendations, to be summarized shortly, it outlined the importance of EPO for accountability reasons: taxpayer funding of astronomy is partly related to the social good of knowledge transfer. LRP2010 also highlighted that EPO is a dialogue that is both local and national, while simultaneously influencing spheres from the local community through to the federal government. In this context, it was emphasized that outreach is not a "one-off" endeavour, and requires long-term investment of time, effort and money. The last of these factors was contrasted to US-based approaches, where outreach funding ("broader impact" in NSF terminology) is often a component of research funds and facility operations.

Many of the key reasons for outreach were discussed in detail in LRP2010. Astronomy's accessibility, appearance in school curricula, and position as a cornerstone of scientific literacy remain unchanged. Numerous active STEM professionals continue to describe their own interest in astronomy as having been a gateway to further study in STEM fields. Indeed, in many funding discussions, the "gateway" viewpoint is considered one of the key factors in funding new astronomy research. The amateur community registered within the RASC and FAAQ alone, is upwards of 6,000, dwarfing the professional community by at least ten to one and regularly contributing in a number of science areas such as comet discovery and variable stars. Readership of SkyNews is even estimated to be as large as 80,000. But beyond such considerations, astronomy remains a unique point of commonality across cultures, with sky lore, myth, and modern research knowledge being pathways to begin conversations on differences and similarities between peoples.

Despite the significant outreach efforts made by astronomers in 2009, at that time it was clear that astronomy did not feature significantly in Canadian news reporting as compared to the BBC. A simple analysis showed that 1/5th as many astronomy stories appeared on CTV and CBC, as compared to the BBC. Although social media was growing in popularity at that time, it was not the universal force that it is in 2015.

Given these contexts, the LRP2010 recommendations were (1) that graduate programs consider including elements of outreach to their programs, (2) the development of an astronomycanada.ca website and (3) the potential value of investing 1.5% of research grants into outreach activities, a similar amount to that recommended in US NSF grants.

As of 2015, outreach is arguably in a somewhat better situation than it was five years ago primarily because of increased

institutional support. Yet there is no true national coordination of efforts, and the astronomycanada.ca website is undeveloped. While the aforementioned institutionally supported initiatives have blossomed, efforts by CASCA and to a certain extent individual researchers have had a challenging time. The problem for both individual researchers and CASCA is financial. Calls for monetary support of outreach via individual NSERC grants have gone unheeded for 15 years now, while CASCA does not have sufficient revenues to support full-time personnel. As a result, CASCA is now supporting initiatives by spending-down revenue on endowment funds that had accumulated over the past decade, something that is clearly not sustainable in the long term. Also, while fundraising is frequently discussed at a local level, and successful campaigns have been a driver behind new initiatives, it is challenging at the national level. Clarifying CASCA's goals for EPO would thus bring clarity to community expectations of what role CASCA should play.

Recommendation: CASCA draft a mission statement on its EPO activities and goals.

Before reviewing changes in the EPO landscape, the MTRP would like to commend all volunteers and staff for their activities and efforts in making astronomy outreach in Canada successful! The legacy of IYA continues.

Communications in 2015

The growth of social media has precipitated an overwhelming change in the communication landscape since 2010. Social media has driven political revolutions, activism, and frequently reshaped mass media coverage of topics. As well as the positives, there have also been negative consequences, such as the spread of disinformation and a disturbing rise in online bullying and harassment.

Facebook has been a key player in connecting families and brought most demographics into the fold. The growth of easy to use computing platforms like the iPad as well as mobile access, has also spurred uptake. Facebook now estimates that 14 million Canadians use it every day, with a total of 18.5 million users. Putting the numbers in perspective; over half the Canadian population is now estimated to have a Facebook account. Facebook advertisements can be specifically targeted to interests and geographic locations — they are extremely effective at reaching desired audiences.

A number of projects have connected with the public in innovative ways. Leading the vanguard in this area was arguably Chris Hadfield, who in the space of five months built up over a million twitter followers and generated enormous media interest. The ESA Rosetta mission also crafted a carefully orchestrated campaign of cartoons and messages that caught the public imagination. Equally impressive was the approach used by the New Horizons team, who intelligently relied upon the public's view of Pluto as an "underdog" to craft a clever and engaging social media strategy. Their tweets and posts often drew on popular culture references to widen the audience. With social media interest often leading mainstream stories, all these projects featured heavily in the mainstream media. However, these three examples show that a good social media strategy requires content and talent.

In the Canadian astronomy community, individual and institutional uptake has been noticeable. There are at least two, and likely more, astronomers with thousands of followers, as compared to the CASCA twitter account (@AstroCanada) which at the time of writing has 800. For comparison, l'Observatoire du Mont-Mégantic has over 1,200 followers and the Dunlap Institute twitter account has close to 1,000 followers. Local Facebook pages have also garnered significant participation, for example the Astronomy Nova

Scotia page has almost 800 likes, and Facebook arguably remains the best way to reach a large audience because of the wide usage.

Recommendation: *Social media should be considered a key component of organizational outreach strategies. Appropriate resources, specifically funds, talent, energy, and time, should be allocated.*

In the national and local media the coverage of astronomy is significantly improved. While the transit of Venus in 2012, being the last for over 100 years, garnered vast crowds, even more common events like lunar eclipses are generating media interest. LRP2010 noted that CTV News carried only seven astronomy stories on its website, while a search in 2015 reveals over 70 (for the year). Some astronomy commentators are appearing almost weekly in the media. While social media has played a part in improving this, there may perhaps be elements of politics involved as “science muzzling” was a common thread in much media discussion through 2013–15. Nonetheless, the new visibility is extremely welcome and we hope it continues.

Changes in institutional approaches to funding outreach

Although there have been many positives, one particularly negative event stands out, namely the closure of the Centre of the Universe at NRC Herzberg. Previous LRP recommendations had strongly backed the value of government-led outreach. Ongoing efforts to restore science programming at the DAO are being led by a volunteer group, The Friends

of the Dominion Astrophysical Observatory Society. At the time of writing, a series of fundraising events, including an internet crowdfunding project are underway. Whether new government policy and funding will redress this very significant loss of a key outreach facility remains to be seen.

Returning to the positives, many, if not all, of the new institutes devoted to astronomy or space science have incorporated outreach into their mandates. Funding for individuals responsible for outreach has thus been enabled, with the Dunlap Institute, the Centre for Planetary Science and Space Exploration at Western University, and the McGill Space Science Institute, among others, all employing individuals in outreach capacities. New hardware investments have also been welcomed including new planetariums/theatres at the University of Toronto, Montreal (Rio Tinto Alcan) and McMaster University, as well as major observatory building and retrofits at Simon Fraser and Saint Mary’s. Unsurprisingly, social media presences for these institutes and initiatives are generally very well done.

CASCA has also increased its own funding to outreach by providing \$20K per year to the highly successful Discover the Universe project¹³ (DU). This project, a legacy of IYA, that arose out of a collaboration between CASCA, the RASC, and FAAQ, has also received funding via an NSERC PromoScience grant. DU’s goal is education of teachers, and while this is not unique, DU has developed an online delivery system, including lectures and interactive chat, typically over a three week period, to help build a sense of community between the participants that transcends geography. Participants learn about common introductory topics such as the constellations, motions of the Earth and phases of the Moon and are provided with many in-class activities and digital


resources. Through its commitment to bilingualism and quality of presentations, the program has attracted funding and promotion from the IAU, to reach a total of over 900 educators in Canada and across the globe.

Unfortunately, as of 2016 NSERC PromoScience has declined to continue funding the DU project and the Dunlap Institute has stepped in to keep the project funded in the short term. However, this highlights a key difficulty with outreach initiatives: If seed funding is provided, while content and operations require continued staffing, the withdrawal of funding will inevitably lead to closure. To be truly effective, outreach efforts require continued financial support to ensure materials and messages evolve along with the science they are promoting.

Despite individual NSERC grants not being augmented for outreach purposes, and concerns about support of the DU project, the MTRP commends NSERC’s PromoScience program and applauds recent statements that this program is likely to be augmented. Similarly, despite recent and highly visible setbacks, the NRC has played a key role in outreach efforts and the MTRP is highly supportive of re-establishing these programs.

Recommendation: *NSERC commit to expanding the PromoScience program budget, while NRC return to funding astronomy-related outreach at levels similar to the 2000–10 decade.*

¹³ <http://www.discovertheuniverse.ca/>



*Advances in observational astronomy depend
critically on access to the best and newest facilities*

5 Ground-based Facilities

5.1 World Observatories

5.1.1 TMT

LRP2010 identified participation in the next generation of very large optical/near infrared telescopes (VLOTs) as the top priority for ground-based optical-infrared astronomy through the following recommendation:

Timely access to a VLOT remains Canada's number one priority for large projects in ground-based optical-infrared astronomy over the next decade. Canadian participation in a VLOT needs to be at a significant level, such that it will not be treated as a "lesser partner" in scientific, technical, and managerial decisions.

The TMT is a diffraction limited optical/near infrared telescope with a 30 m segmented primary mirror. It is one of three large aperture telescope facilities being developed by various international partnerships. LRP2010 conducted a detailed review of the European Extremely Large Telescope (E-ELT) and the implications of joining ESO, as compared to continued involvement in the Thirty Meter Telescope (TMT). The conclusion was continued participation in TMT subject to the project moving forward promptly:

If by early 2012 it appears that a 2014 construction start for TMT will not be feasible, then the LRPP recommends that we take steps to become a partner in the E-ELT project by joining ESO, and that we discontinue our partnership in TMT.

One of the primary drivers behind this conclusion was that Canadian scientists and industry have played leading roles in its design. TMT is thus viewed as holding the greatest scientific promise and technological interest for Canada. The four highest priority Canadian science cases (described below) all benefit from observations that are aided by adaptive optics, and TMT will correct and concentrate light from a point sources better than any other competing VLOT observatory. TMT also has a balanced design including non-adaptive observing modes, and the ability to deploy quickly to targets of opportunity. It will be the cornerstone for a suite of Canadian observing facilities that include optical and long wavelength ground based telescopes, as well as space satellites, all of which will provide highly selected targets to the TMT.

Canada committed \$243.5M to the TMT project in April 2015. These funds will be spent primarily in Canada and will enhance our industrial capability and competitive edge for future contracts. Canada's largest contribution will be the enclosure (see Figure 3), a precision steel structure to be built by Dynamic Structures Ltd. (Port Coquitlam, BC) at a cost of close to \$150M. Approximately \$70M is earmarked for Canadian instrumentation work, including the sophisticated adaptive optics system (NFIRAOS) being built at the NRC Herzberg (Saanich, BC). The remaining funds are for centralized project management and infrastructure costs. These funds will be distributed over the nine year construction period, but somewhat front end weighted, driven by the enclosure which must be in place before the telescope is assembled inside it. This funding commitment, with the early investments of nearly \$30M and fundamental contributions to the design of the TMT facility and instruments, mean that Canada has secured a "second to none" share at ap-

proximately 15% of this \$1.6B project. It is worth noting that the TMT construction is a one-time cost for a project with a lifespan > 50 years. The TMT partnership includes Canada, China, Japan, India, the University of California and the California Institute of Technology, all of whom have committed construction funds and share in the scientific, technical, and managerial decisions.

Partnering in the TMT has been Canada's top priority for ground based astronomical facilities over the past decade. The MTRP reaffirms the high importance of the scientific and technological priorities of the TMT facility, and recognizes the enormous economic benefits to Canadian industry. The MTRP also thanks the Canadian government for financial support and commends the Coalition for Canadian Astronomy for helping to secure Canada's second to none partnership in the TMT project

The science cases of the strongest interest to Canadian astronomers remain the same as described in the LRP2010, and continue to make the TMT project the top priority in ground based optical/IR astronomy in Canada going into the future. These include, (1) Extrasolar planets and the Search for Life: detection of new planets and biomarkers in their atmospheres, (2) First Light: the exploration of first stars and galaxies to form in the early Universe, (3) Super massive Black Holes at cosmological distances, as well as the centre of our own galaxy, and tests of general relativity, and (4) Cosmology and Dark Energy: the discovery and identification of distant type Ia supernovae, to map out the dynamics of the Universe as a function of its age. All of these scientific goals include synergy

with existing observatories (such as HST, Gemini, CFHT and ALMA) that have contributed to the target selections and instrumentation requirements for TMT, and with future observatories that can probe targets at different wavelengths or provide a larger context from wide field surveys (such as JWST, MSE, and SKA). Furthermore, astronomical instruments will be located on Nasmyth platforms, permitting large instruments with quickly accessible components and rapid switching from the adaptive optics facility to various instruments (< 10 min) or between different targets (< 5 min). Rapid switching between instruments or targets means the TMT will be able to respond to targets of opportunity, such as transiting planets, newly discovered supernova events, or other rapidly variable astronomical phenomena, and to respond to changing weather conditions in order to exploit the full potential of the observatory. The TMT will provide new observational

opportunities in essentially every field of astronomy and astrophysics, and it is expected to be the powerhouse that leads to new paradigm-shifting and prize winning scientific research in the future.

The TMT is also an ideal example of how investments in science can deliver new commercialization opportunities to Canadian industry. The innovative integrated dome and support design by Dynamic Structures Ltd (DSL) is now iconic of the TMT, and represents a high profile symbol of Canadian technological prowess. Projects like this have helped DSL develop techniques that have contributed to it becoming a world leader in the design and construction of media-based attractions for the entertainment industry. Canadian expertise in adaptive optics, being developed for the TMT at the NRC Herzberg, includes algorithms, as well as data analysis and simulations on petascale supercomputers that will find ap-

plications in areas from medical imaging to fluid dynamics. This enhanced technology base can allow Canadian industries to tackle new commercial opportunities in space technology and products in optical communications, which are important to successfully compete globally. All the work slated for Canada is in highly skilled sectors, and previous investments in astronomy have a proven track record of delivering long term economic spin offs. These provide real opportunities to attract and retain highly skilled workers into Canada's workforce, as well as build connections – academic and industrial – with the existing and emerging economic powers of Asia: China, India, and Japan, all TMT partners.

The TMT initiative in Canada was overseen by ACURA (the Association of Canadian Universities for Research in Astronomy and its 20 member universities), working with the Coalition for Ca-



Figure 3. Design drawing of the dome of the Thirty Meter Telescope (TMT). The dome structure has been designed by the Canadian company Dynamic Structures Ltd. (DSL, Port Coquitlam, BC). Credit: TMT International Observatory.

nadian Astronomy, CASCA and Industry. Their work has been extremely important in negotiating Canada's partnership in the design and development of the TMT project, in securing the Canadian financial commitment to its construction, and resolving Canada's share of the scientific access and management impact. Now that funding is committed, to be managed and directed through the NRC, the next step for the university sector is to maximize the scientific returns by ensuring all Canadian researchers are aware of the many opportunities made available through the TMT. This also includes contributing to second generation instrumentation design and development, in both the scientific and industrial communities. Past funding for TMT design work has come from NRC, CFI, and NSERC, with additional provincial and university contributions. A combination of these sources could leverage Canada's outstanding industrial innovation and expertise through contributions to new instrumentation projects and upgrades, delivering new commercialization opportunities to Canadian industry.

Construction of the TMT began in October 2014 with a ground-breaking ceremony, however as of April 2015, protests on Maunakea have halted on-site work and on December 3, 2015, the Hawaii Supreme Court required a re-application for the construction permit. While the TMT management considers their next steps, the Canadian community remains very supportive. The TMT will provide scientific and industrial opportunities for Canada in essentially every field of astronomy and astrophysics, as well as

contribute to innovative technologies and industrial applications with real economic impacts for Canada.

Recommendation: *With access to a VLOT being the number one priority for ground-based optical-infrared astronomy, the MTRP reaffirms the importance of maintaining a “second-to-none” share in TMT. Since partner shares will also factor in future contributions to the observatory, the MTRP therefore strongly endorses ongoing development of second-generation instrument concepts and encourages the various teams to pursue funding.*

5.1.2 SKA

LRP2010 made the following recommendation concerning the SKA:

The LRPP reaffirms the importance and very high priority of Canada's participation in the SKA, which it anticipates will become the top priority following VLOT. Canada should continue its current path in the engineering design and prototype development of SKA elements, leading to participation in the pre-construction design phase and should continue to seek opportunities to build components where Canada has experience and an international reputation. SKA R&D is the highest priority medium-scale project over the next decade. The decision as to how and when Canada should enter the construction phase of SKA should await further reviews of SKA project development, a more accurate cost estimate, better understanding of international prospects, and a better knowledge of timing for funding a construction start.

There have been several important developments in the SKA project since LRP2010. The SKA Organisation (SKAO) was established as a legal entity in 2011, moving the project into a pre-construction design stage. Canada is one of ten member countries of the SKAO, with its interests represented through two

directors on the SKAO Board. Canadian participation in the SKA is advised by the ACURA Advisory Council on the SKA (AACCS), which includes representatives from universities and industry. SKA site selection occurred in 2012, with Australia and South Africa each hosting components of the observatory. SKAO headquarters were chosen to be at Jodrell Bank, UK, in early 2015.

The SKA will be deployed in phases. The first phase, SKA1, will have ~10% of the final SKA sensitivity and a cost cap of €650M (at an exchange of \$1.50 CAD to €1, this is very close to \$1B CAD). The full sensitivity of the SKA will be reached in a second phase, SKA2, whose scope, cost and timeline are yet to be finalized. The MTRP has therefore focused its assessment of Canada's role in the SKA project on SKA1.

The SKA1 design separates into two distinct components: SKA1-Low, located in Australia and comprised of 128,000 dipole antennas working in a frequency range of 50–350 MHz and SKA1-Mid, located in South Africa and comprised of 133 15 m dishes supplemented by the 64 12 m dishes in the MeerKAT array. SKA1-Mid will have three operational bands between 350 MHz and 13.8 GHz. This configuration was arrived at as a result of a re-baselining process in 2015 that built upon earlier design reviews in 2014. Earlier proposals also included the SKA1-Survey component, an array of dishes with wide-field phased-array feeds to be sited in Australia, which has been deferred following the re-baselining; although phased array feed development will continue in anticipation of SKA2. The re-baselined SKA1 remains a transformational instrument compared to the cur-

rent state-of-the-art: SKA1-Low has eight times the sensitivity and 135 times the survey speed of LOFAR, and SKA1-Mid has five times the sensitivity and 60 times the survey speed of the JVLA

With a baseline design and costing for SKA1 now in place, a timeline for the project has been established. Critical design reviews of SKA1 components will take place in 2016. Tender and procurement for SKA1 construction will occur in 2017 in anticipation of a 2018 construction start, to which the United Kingdom and Australia have already committed funds. Early science will begin in 2020, with construction expected to finish in 2023. Important milestones for the SKA should therefore be reached within the next five years. While some schedule slip remains likely, Canada's role in the project needs to be established in this context.



Figure 4 The SKA will consist of two vast arrays of radio telescopes: one in Africa and one in Australia. This artist's impression shows the central core of the SKA-2 African array, to be constructed in the Karoo region of South Africa. Credit: SKA Organisation

There have also been important developments in the design, construction, and operation of precursor and complementary facilities to SKA1 since the LRP. At the intermediate frequencies at which SKA1-Mid will operate, the wide-field Australian SKA Pathfinder telescope (ASKAP) and cryo-cooled MeerKAT array are being constructed at the Australian and South African sites, respectively; they represent ~10% of SKA1 in terms of sensitivity and survey speed. Commissioning observations are underway at both facilities, and full science operations are expected in 2017. A variety of other pathfinder facilities will soon begin operating at frequencies that overlap with SKA1-Mid, such as FAST and APT. FAST will have a higher sensitivity than SKA1, but a much narrower field of view; SKA1 is therefore by far the superior survey machine. The nascent ngVLA concept may overlap with SKA1-Mid at some frequencies but its timeline lags considerably behind it, resembling that of SKA2.

The landscape for radio facilities in the low-frequency regime in which SKA1-Low will operate has evolved dramatically in recent years. The MWA has been fully operational at the Australian SKA site since 2012, and has recently been awarded funding to double the number of tiles and baselines. A Canadian consortium led by the University of Toronto participated in and contributed matching funds to the MWA upgrade proposal. Science operations are also well underway with LOFAR and PAPER. Looking into the future, the HERA collaboration has recently received seed funding through the US mid-scale astronomy program to design a compact drift-scanning array to measure the epoch of reionization (EOR) power spectrum with a similar sensitivity to, and on a similar time scale as, SKA1-Low. The most significant differences between HERA and SKA1-Low are the distribution of the collecting area and the operating frequency range; while the HERA experiment is designed specifically to measure EOR statistics, the longer baselines and broader frequency coverage of SKA1-Low afford both EOR imaging

and EOR statistics as well as a variety of other low-frequency science questions to be tackled. Thus while the relatively low cost of constructing large collecting areas at these frequencies implies that experiments targeting specific aspects of SKA1-Low science may emerge in the coming decade (e.g. the potential highlighted in section 5.2.4 CHIME technology or calibration algorithms); SKA1-Low is currently the only general purpose low-frequency facility on the horizon. The MTRP therefore reaffirms the importance of the SKA:

***Recommendation:** The MTRP re-iterates the very high importance of Canada's technological and scientific participation in the next generation of radio telescope facilities. With TMT construction funds committed, access to the capabilities provided by SKA1 in the next decade is the top priority for new funds for ground-based astronomy. The MTRP re-iterates the high priority of mid and low-frequency radio R&D, and in particular the development of key technologies for SKA1 tender and procurement.*

Since the LRP2010, Canada has maintained its leadership role in the engineering design and prototype development for the SKA. In joining the SKAO in 2011, Canada agreed to deliver €8M of in-kind work to the SKA pre-construction phase. This work is taking place in three of the ten design consortia responsible for the detailed design and costing of SKA1. NRC Herzberg leads the Central Signal Processing Consortium, and is responsible for the SKA1-Mid correlator and beamformer

design with industry partner MacDonald Dettwiler & Associates (Surrey, BC). Within the DISH consortium, NRC has developed rim-supported antennas, low-noise amplifiers, digitizers, and secondary reflectors for use on SKA1-Mid. The antenna design (Figure 5) was not chosen in a decision made in December 2015, and Canada will not contribute to this aspect of the SKA development. However, other important areas of application for the elegant single-piece antenna design are already being considered. Several major industry partners are engaged in the DISH consortium effort, including SED Systems (Saskatoon, SK), Nanowave technologies (Etobicoke, ON), and Canadian Circuits (Surrey, BC). NRC Herzberg is also testing room-temperature and cryo-cooled phased array feed designs for SKA2. Canada's technological work in all of these areas will maximize the effective collecting area and field of view and minimize the system temperature of SKA1-Mid; Canadian innovation is therefore contributing directly to the SKA1-Mid sensitivity and survey speed.

The major scientific themes for the SKA are probing the cosmic dawn, galaxy evolution, cosmology and dark energy, the origin and evolution of cosmic magnetism, strong field tests of gravity, and the cradle of life. A revised science book for the SKA was published in 2015, demonstrating the tremendous breadth of science results that SKA1 will deliver: imaging the EOR and Cosmic Dawn, finding and timing millisecond pulsars to test gravity, tracing the cosmic evolution of interstellar and intergalactic magnetic fields, detecting atomic gas reservoirs in galaxies out to $z \sim 3$, and measuring the star formation history of the Universe out to $z \sim 6$ are but a few. Canadians participate in 11 of 13 science working groups that are developing key science projects to address the highest priority science objectives for SKA1. As a result, Canadian astronomers are poised to be involved in every major survey that SKA1 will undertake, and Canadian proposals for SKA1 PI-driven science should also be competitive.



Figure 5. Caption: Dish Verification Antenna #1 at NRC-DRAO, a novel 15 m diameter, rim-supported composite reflector. Its high performance, low cost design has a number of potential applications beyond the SKA. Credit: S. Dougherty

Beyond simply participating in SKA1 science working groups, Canada has the expertise to play a world-leading role in several of the key science projects that will emerge from them: pulsar searches and timing experiments to carry out strong-field gravity tests, radio continuum and polarimetry surveys to measure cosmic magnetism, transient studies to explore the variable radio universe, and both resolved and unresolved atomic gas surveys as a probe of galaxy evolution and cosmology. This expertise is reflected in the Canadian leadership of SKA precursor and pathfinder surveys, as well as in the SKA1 working groups themselves. For pulsar searches, cosmic magnetism and galaxy surveys in particular, the re-baselined SKA1 will be far superior to any

other current or planned facility, while pulsar timing with SKA1-Low will be complemented by CHIME's capabilities in the northern hemisphere. The science case for SKA1 is therefore well-aligned with both Canadian research interests and areas of considerable Canadian expertise.

Funding for the construction and operation of the SKA is based on the principle of common access to the SKA telescopes by all the contributing members. Further, the expectation is that much of the work will be done by large, cross-partner teams working on large-scale observational programs. As a starting point for detailed negotiation, the contributions for each member state are to be based on the number of astronomers

each has admitted to membership in the IAU. Those member countries that are hosting common SKA infrastructure (the two telescopes and the SKA HQ) are expected to contribute more. The premium recognizes the benefits accruing from the investments of the other members. In this model, construction funding in the range of €30M – €65M will therefore be required from Canada, spread over a period of several years. These funds could be provided by in-kind contributions of Canadian-developed key technologies, an ensemble of which is being prepared for tender by NRC. Operations costs are considerably more uncertain, and driven in part by the electricity consumption of this compute-intensive instrument. Current estimates imply that Canada's annual contribution to SKA1 operations would be in the €4M – €6M range. In the context of the overall envelope of operations budgets, the MTRP highlights that access to new "world observatory" class facilities inevitably means that new operations funding will be needed to cover these costs as well as Canada's share of the operating costs for other facilities in the next decade. The time scale for the delivery of both construction and operations funding remains uncertain, but a commitment will be required soon if construction and early science begin in 2018 and 2020, respectively, as currently planned by the SKAO.

The MTRP concludes that Canada is playing a leadership role in both the technological and scientific development of SKA1. Canada's strengths in correlator, low noise amplifier and digitizer technology have forged strong partnerships between NRC and industry that are directly improving SKA1 performance; Canada is well-positioned for tender and procurement of SKA1 construction contracts. SKA1 key science objectives align well with Canadian interests and expertise in several different fields and Canada has the capability to lead some of the highest priority surveys that SKA1 will undertake.

Member funding for the current SKA organization, a company limited by guarantee registered in the UK, is approved through to the end of 2017. It is anticipated that by 2018, the governance will transition to an intergovernmental organization (IGO) defined by a binding Convention (Treaty) under international law. In Canada, governmental approval via a memorandum to cabinet must be obtained before treaty negotiations can be entered. At present, no organization within Canadian astronomy has this authority, and hence Canada's influence on the future governance of the SKA project is limited. Therefore, the MTRP makes the following recommendation:

Recommendation: *The MTRP strongly recommends that Canada enter into negotiations to join the intergovernmental organization that will oversee SKA1 construction and operations starting in 2017. An alternative to a treaty may be needed for Canada to join SKA1; this alternative must not significantly compromise Canada's role in SKA1 governance, access, or construction tender and procurement.*

5.1.3 ALMA

ALMA was the top-ranked priority for new ground-based facilities in LRP2000. A collaboration involving North America, Europe, East Asia, and Chile, the Atacama Large Millimeter/submillimeter Array (ALMA) is the first example of a “world observatory”. ALMA consists of 66 radio antennas located on a 5,000 m plateau in northern Chile. With operating wavelengths from 3 mm to 350 μm and angular resolution from a few arcseconds to tens

of milli-arcseconds, it is one of the most powerful telescopes in the world. Canada is a partner in ALMA and in collaboration with the United States and Taiwan forms the North American region of ALMA. Canada contributed to ALMA construction by building the Band 3 receivers for all 66 telescopes and by contributing to the development of software, primarily in the area of off-line data reduction and the archive. The total Canadian contribution to ALMA construction was \$20M (US\$, Y2000). Canada also contributes annually to ALMA operations, both in cash and in-kind; the Millimetre Astronomy Group at NRC Herzberg collaborates with the National Radio Astronomy Observatory in assisting ALMA operations through the North American ALMA Regional Center.

ALMA has been designed to be a powerful and versatile scientific facility, able to make transformative discoveries across a wide range of scientific fields. ALMA has been taking data in “Early Science” mode since October, 2011 and has delivered exciting new results in such diverse fields as debris disks, star formation, merging galaxies, and galaxy formation in the distant universe. Probably the single most iconic result to date has been the spectacular image of the protoplanetary disk around the young star HL Tau (see Section 3.1 Are we alone?) showing broad rings and gaps that are evidence for the sculpting of the disk by young unseen planets. Other highlights include the discovery of spiral structure in the envelope of the evolved star R Scl, the determination of the mass of the central black hole in the spiral galaxy NGC 1097, and sensitive measurements of large numbers of young galaxies in the early universe. Highlights of papers led by Canadian astronomers include resolved images of the debris disk around the young star Au Mic, detailed images of the highly obscured galactic nuclei at the heart of the most spectacular nearby merger remnant Arp 220, and dramatic images of young galaxies in the early universe distorted by the effects of gravitational lensing.

Since LRP 2010, ALMA has made major progress: construction has been completed, many key observing modes have been commissioned (including the longest baselines), and four calls for proposals have been issued. The Cycle 2 and Cycle 3 calls for proposals received the largest number of proposals ever received by a single observatory, with 1,578 proposals submitted to the April 2014 call, exceeding previous records set by the Hubble Space Telescope. The large demand for ALMA observing time (time requested versus time available resulted in oversubscription rates of a factor of four in the most recent calls) shows that ALMA is a telescope that is accessible to a large community of astronomers and is succeeding in its goal of broadening its appeal beyond the “black-belt” interferometry community. Within Canada, 79 astronomers from 18 different institutions were PIs or co-Is on submitted ALMA proposals in Cycle 3.

Now that construction is completed and operations are well underway, attention is turning to development work that can improve ALMA's performance or extend ALMA's capabilities. These development projects will be funded out of ALMA operations and can include both hardware and software initiatives. Canadians at NRC Herzberg and universities have participated actively in several development studies to date. NRC Herzberg continues to collaborate in efforts to develop new ALMA Band 1 (7 mm) receivers and is in a good position to provide key components for the production run if this development project goes forward. Another potential path for Canadian involvement is in improvements to the usability and functionality of the ALMA archive, given the extensive expertise in archive development in Canada. For example, the current ALMA archive has no preview capabilities and provides only very limited search functions, which makes it hard to conduct extensive searches of the archive.

Thus, two key Canadian priorities emerge for the next five years: (1) identifying components of the ALMA development program in which Canada can play a significant role, including stimulating expertise in sub-mm instrumentation in order to capitalize on future opportunities with ALMA; and (2) reaching the widest possible community of potential users and keeping them fully trained and engaged in ALMA, as new capabilities become available. The MTRP re-affirms the recommendation from LRP2010:

Recommendation: *Canada should participate in a bid for ALMA development funding to build the ALMA Band 1 receivers, which would take advantage of Canadian skills and experience developed during the design and building of the Band 3 receivers. In addition, Canada should proceed quickly to identify other short-term and longer-term priorities for ALMA development work.*

5.2 International and National Facilities

5.2.1 CFHT and MSE

CFHT

The Canada-France-Hawaii Telescope (CFHT) is a 3.6 m telescope on Maunakea, Hawaii. Over the past four decades, CFHT has been responsible for many major discoveries. CFHT (and Canada) have led the way in the development of techniques for the discovery of extra-solar planets, deep surveys of galaxies in the Local Group, the Virgo Cluster, and at high redshifts, while the Supernova

Legacy Survey has led to the best characterization to date of the nature of dark energy in the Universe. The impact of the CFHT (in papers and citations) has been comparable to that of larger eight-to ten-metre facilities, due in large part to the quality of the site, investments in MegaCam to exploit the advantages of the site, and importantly that the collaboration made a commitment to survey science. Improvement of image quality has also been a continuing goal of the observatory (see Figure 6). Furthermore, the experience of developing state-of-the-art instrumentation for CFHT has paid off in placing Canada in the leading position to develop new instruments (e.g., GMOS, GPI, and GHOST), and the adaptive optics systems for the Gemini-North telescope (ALTAIR) and the TMT (NFIRAOS).

LRP2010 continued the strong support for the observatory with the following recommendation:

Canada should continue to be a major partner in CFHT, and should support and participate in new instrumentation projects (specifically 'Imaka, SPIRou, and GYES). These instruments should have a five year operations window prior to any anticipated redevelopment of the CFHT site.

SPIRou was selected and is now well into the construction phase. It is a near-infrared high-resolution spectrograph that will be capable of detecting Earth-like planets in the habitable zone of low-mass stars, and it will also investigate the role of magnetic fields in the star/planet formation process. Additionally, new filters have reinvigorated the potential of MegaCam, including a new u-band filter that leverages CFHT's excellent sensitivity in the UV, and a new narrow band Ca H&K filter which can be used to measure stellar photometric metallicities and search for very metal-poor stars. The new 300 m fibre feed to ESPa-

DOnS from the Gemini-North 8-metre telescope (GRACES), developed in Canada and a key example of inter-observatory co-operation, has been found to have similar sensitivity as the best high resolution spectrographs on Maunakea (HIRES at Keck, and HDS at Subaru), at wavelengths above 500 nm. The success of GRACES means that the CFHT community will be compensated for the use of ESPaDOnS through access to Gemini in future mini-calls for proposals. In addition, SITELE (a visible imaging Fourier Transform Spectrometer) is a new CFI-funded CFHT guest instrument. SITELE was built in Canada (Laval & ABB-Bomen), commissioned at CFHT in July 2015, and opens a new unexplored discovery space: integral field spectroscopy in visible light over a wide field (11 arcminutes). It will be used to study the dynamics and abundance trends of galaxies from their emission lines, as well as the physics of the interstellar medium.

Going forward, CFHT plans to increase its commitment to larger survey programs (more like the CFHT Legacy Surveys). This will be accomplished by allocating 429 nights (from the Canadian and French agencies, plus potential contributions from other partners) over the next three years (2017–19). Another call for large program after 2017 is anticipated.

As LRP2010 was being completed, a new concept emerged, initially referred to as ngCFHT (the next generation CFHT). The ngCFHT concept was based on the information that the existing pier and building can support and house a telescope of aperture up to 15 m, and if that is coupled with a wide field multi-object spectrograph (WF MOS), then it becomes possible to collect high and low resolution spectra of ~4000 very faint targets over a 1.5 degree field. Such a capability is not currently available anywhere, and yet is strongly synergistic with the requirements of several high profile survey science concepts in both galactic and extragalactic astrophysics (below). This project is currently being developed as the Maunakea



Figure 6. CFHT dome interior showing the newly installed vents that have significantly improved image quality. Credit: CFHT/Tom Benedict.

Spectroscopic Explorer (MSE, discussed below). Tension now exists between completion of long term and large projects at CFHT and the redevelopment of the site for MSE. The total number of hours required for the large and long-term programs, including that associated with SPIRou, need to be carefully determined and secured. The CFHT management has worked hard to balance these concerns and various priorities.

Recommendation: *Canada should continue to be a major partner in CFHT, supporting its facility instrumentation project, SPIRou, and completion of the planned large surveys, as a 3.6 m telescope. Slippage in these projects should not delay redevelopment opportunities and priorities.*

MSE

The Maunakea Spectroscopic Explorer (MSE) is an ambitious redevelopment project to transform the CFHT 3.6 m telescope into an 11 m facility, with a dedicated wide field multi-object spectrograph (WF MOS). The idea of redeveloping the excellent CFHT site has been discussed in the Canadian community for nearly two decades, and the concept of a dedicated WF MOS facility was identified for detailed investigation with the following recommendation in LRP2010:

The LRPP recommends that Canada develop the ngCFHT concept (science case, technical design, partnerships, timing).

Such a capability is of great interest to the international community and has been discussed in detailed planning processes in both in the US,¹⁴ Europe¹⁵ and Australia.¹⁶ It is therefore unsurprising that the MSE project has received considerable international interest. A feasibility study was carried out in 2011–12 to investigate the key science drivers and major technical challenges, and included contributions from scientists and engineers in Canada, France, and 10 other countries. In September 2013, the CFHT SAC recommended to the Board that a Project Office lead further developments. The Project Office was initiated in May 2014 in Waimea, HI, coinciding with the renaming of the ngCFHT as the MSE.

The MSE Project Office is leading the design phase by producing a construction proposal for 2017: specifically, the Project Office is leading the development of the Detailed Science Case and the Science Requirement Document, the operational concept, system architecture, design concepts, and the permitting process (in collaboration with the Office of Maunakea Management and other

Hawaiian interest groups). In addition to providing a detailed cost and schedule, the Project Office is also leading the partnership development effort. Currently, the science team consists of 80 members from Australia, Canada, China, France, Germany, Republic of Korea, Hawaii, Italy, India, Japan, Spain, Taiwan, the UK, and the USA. All science team members have had the opportunity to engage in the activities of the Project Office. As of November 2015, the total estimated cost is \$250M to \$300M. When this total cost is divided by the number of significant partners (~six) and reduced through reuse of Canada's current investments in CFHT infrastructure, then the estimated cost to Canada is ~\$40M for a "second to none" share. Full science operations are anticipated in 2025.

The science case for MSE is universally recognized by many detailed studies in a variety of countries and observatories. The WF MOS design for MSE would permit measurements of up to 3,400 objects with a spectral resolution range spanning 3,000 to 40,000, simultaneously, in selected wavelength regions from 360 nm to 1.8 μ m. The science cases for MSE include all fields of astronomical sciences; however they are dominated by two top priority projects: (1) exploring the structure, kinematics and chemical evolution of the Milky Way, i.e., Galactic archaeology; and (2) mapping distant galaxies and AGN to study their evolution through cosmic time. A 10 m class telescope equipped with a WF MOS-like instrument would also have a transformative impact in a wide range of fields, including stellar structure and evolution, transient phenomena, large-scale structure, AGN physics, nature of dark matter, and the epoch of reionization.

MSE has broad international interest because it maximizes aperture size, field of view, multiplexing and observing frac-

tion when compared with all other optical spectroscopic facilities (that exist or are in design). MSE will explore the faint Universe that is beyond the grasp of any two- to four-metre spectroscopic surveys (4MOST, WEAVE, GALAH), e.g., in-situ analysis of the chemical evolution of the outer halo stars at ~100 kpc, and statistical analysis of the broad line regions of high redshift quasars through reverberation mapping surveys. Its location in the northern hemisphere makes it an ideal facility to support target selection for the TMT; also, it overlaps with > 60% of the southern sky, providing excellent collaborative opportunities between MSE and facilities in the southern hemisphere (LSST, ALMA, SKA), as well as space observatories (JWST, WFIRST, Kepler, TESS). No other facility comes close to providing the required follow-up capabilities for these projects; e.g., Subaru-PFS or VLT-FLAMES are only one of several instruments competing for their respective telescope's time, they both have fewer multiplexing capabilities, PFS has a complete absence of high resolution spectroscopic capabilities, and both telescopes hosting the instruments have smaller apertures than MSE. For example, it will be the MSE all sky survey (first data release estimated in 2028) that will provide the ultimate detailed map of the outer halo of our Galaxy, including wide field coverage of accreted dwarf galaxies, stellar streams, and disrupting globular clusters. The nearest analogue in terms of potential impact across subfields is the Sloan Digital Sky Survey, with more than 3,000 papers, covering nearly every field in astrophysics, and with over 100,000 citations. The MSE surveys (both galactic and extragalactic) will include higher resolution spectroscopy at better signal to noise than smaller telescopes and over larger areas. These advances are made possible by the telescopes large aperture and field of view and, in turn, open up new levels of precision astrophysics

14 http://sites.nationalacademies.org/BPA/BPA_087934

15 https://www.eso.org/sci/meetings/2015/eso-2020/eso2020_Bremer.pdf

16 australianastronomydecadalplan.org

and phenomenology. The scientific and collaborative opportunities available to MSE partners are a direct indicator of the strategic relevance of MSE to the future astronomy landscape.

The MTRP thus makes the following recommendation:

***Recommendation:** The MTRP strongly recommends that Canada develop the MSE project, and supports the efforts of the project office to seek financial commitments from Canadian and partner institute sources.*

5.2.2 Gemini

The Gemini Observatory consists of two nearly identical telescopes: one on Cerro Pachon in Chile and the other on Maunakea. They are distinguished from other telescopes in their class by being optimized for thermal infrared observations with excellent image quality, and together offer coverage of the full sky and flexible scheduling opportunities.

Since LRP2010, there has been a major change in the partnership and funding level of the Observatory. The UK left the partnership at the end of 2014, and Australia declared their intention not to continue as a partner after the end of 2015. The departure of the UK left the Observatory with a 23% budget shortfall that has been accommodated with a restructuring and reprioritization of services offered. In 2015 the Korea Astronomy and Space Science Institute (KASI) signed an MoU with Gemini to form a limited term partnership. This is being extended to 2016 and KASI's intention remains to become a full partner in 2017, with a share comparable to that previously held by Australia (~6%). Australia is also continuing as a limited term partner in 2016, albeit at a reduced level.

These changes, together with the appointment in 2012 of a new Director, have led to a significantly different Observatory from the one considered in LRP2010. As part of its restructuring, Gemini has introduced a Science and Technology Advisory Committee (STAC) that reports directly to the Board, and a User's Committee that reports to the Observatory. These have proved successful and are now providing valuable advice and direction. The last five years have also seen great improvement in the instrument suite, particularly on Gemini South. Specifically:

The Gemini Planet Imager was commissioned and available for early science in 2014. This lone survivor of the Aspen program for new instrumentation development is already returning exciting results.

The Gemini South Adaptive Optics Imager is a world-leading AO facility first offered to the community for science in 2013 (Figure 7). It has suffered from a poorly performing laser, and from bright guide star limits; both limitations are being addressed with hardware upgrades.

Gemini Remote ACcess to ESPaDOnS (GRACES) is a collaboration with CFHT that allows users to access the ESPaDOnS high resolution spectrograph via a fibre link to Gemini. It is performing well and proving to be competitive at red wavelengths with HiRES on Keck. It is being offered as a visiting instrument starting in 2015.

Flamingos-2 was commissioned for imaging and long-slit spectroscopy in 2013 and is working well in these modes. Commissioning of MOS mode is planned for the near future.

GMOS-S has been upgraded with red-sensitive detectors, with a similar upgrade planned for the north in 2016.

Gemini has actively encouraged visitor instruments, and successful runs with DSSI and TEXES have taken place.

The next facility-class instrument, GHOST, will be a high resolution optical spectrograph and is currently being built by AAO with a major subcontract to NRC Herzberg. It is expected to be available in 2018.

Planning for the next facility-class instrument after GHOST is underway, with funded, non-competitive feasibility studies. A Request for Proposals to build an instrument defined based on these studies is expected in 2016.

Since LRP2010 Gemini has also introduced innovative ways to use the telescope. The Large and Long Program mechanism allows users to propose to a single TAC for large projects spanning up to six semesters. This mode has been long-awaited (lack of large program opportunities was noted in LRP2010), and is heavily oversubscribed. The Fast turnaround program has monthly deadlines; it is appropriate for shorter projects needing ~10h or less and promises to greatly shorten the time span between an initial idea and the acquisition of data. This mode has generally been met with positive feedback (and was called out as an example in the recent mid-Cycle call for proposals from HST), though some months have seen limited subscription from users. It is being expanded to include Gemini South in late 2015, and with the more capable instrument suite on that telescope the subscription rate to fast turnaround programs is expected to increase.

At the Gemini Science meeting held in Toronto in the summer of 2015, the long-term future of the Observatory was discussed. A panel composed of several Maunakea Observatory Directors acknowledged that a greater degree of cooperation between these facilities in the future will be necessary to minimize operations costs and to compete effectively

for funding in the 30 m telescope era. This is a promising development, as Keck and Subaru have capabilities and operating models that complement Gemini, are well suited to the scientific interests of many Canadian astronomers and, importantly, synergize with TMT in different ways.

In general, Canadians have made excellent scientific use of their time on Gemini. In particular, Canadian astronomers published 22% of all Gemini papers from 2000 to 2012, well above their observing time share during that time. Canadian Gemini papers are cited more frequently

than Gemini papers from other partners, and the median impact of these papers is 2.8 (2008 to 2012), comparable to the overall impact of Keck. The user base in Canada is very broad and includes many students and other young astronomers. Gemini has provided Canadians an opportunity and incentive to collaborate internationally, and almost half of all Canadian proposals are collaborative with other Gemini partners. Canadian oversubscription fluctuates and is generally healthy, but there have been semesters of concern since the Canadian share increased following the departure

of the UK. However, the Large and Long Program opportunity proved popular with Canadians, and two large programs with Canadian PIs were successful in the first round. Canadians are also critically involved in the large GPI campaign. When this participation is included, it is clear that there remains strong demand for Gemini time in Canada.

LRP2010 raised a concern about the US Decadal Survey's recommendation for coupling Gemini governance with NOAO. It is notable that this has not come to pass and the present governance

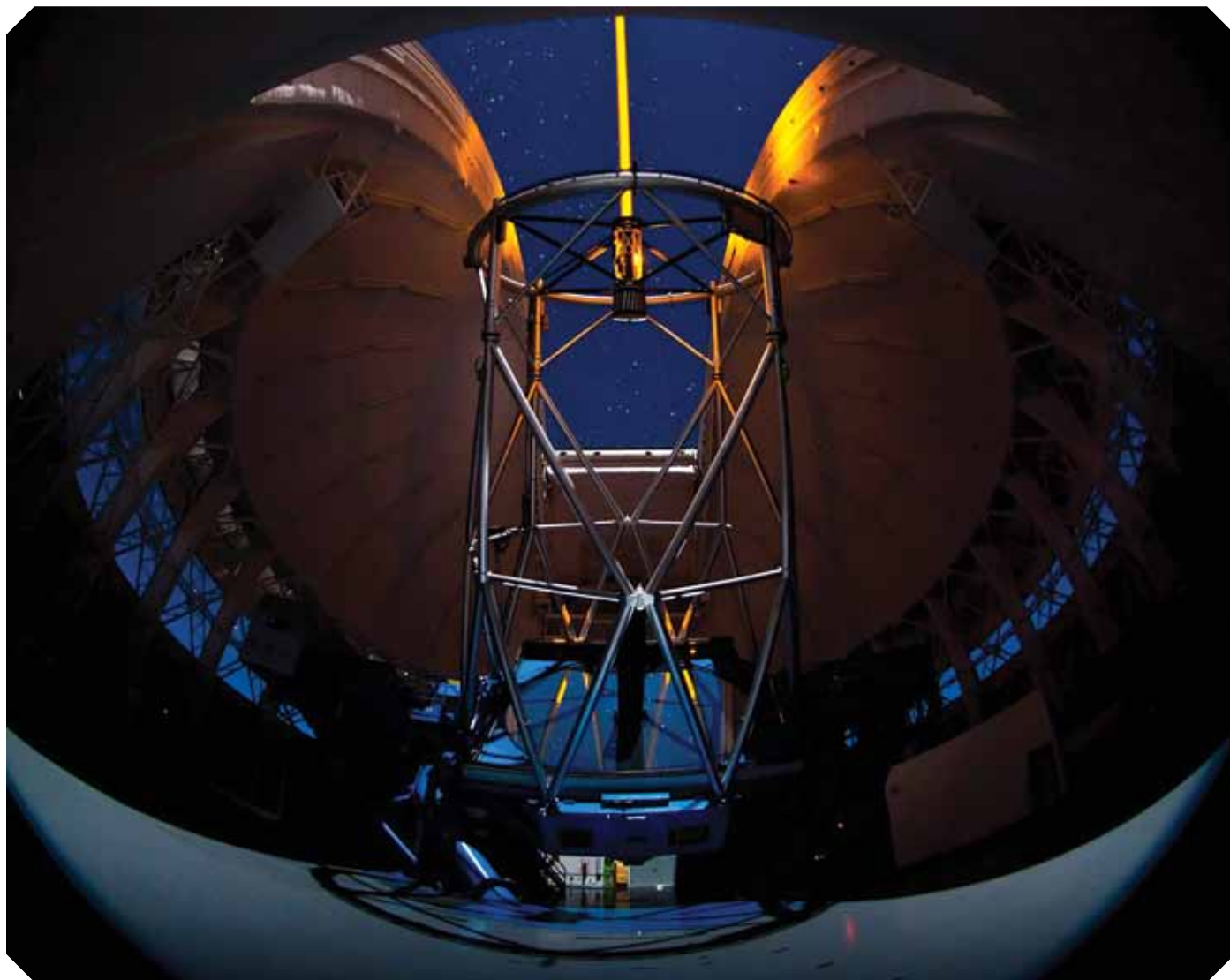


Figure 7. Gemini South with the GEMS adaptive optics laser in operation. Credit: Gemini Observatory

structure will be in place at least until 2022. LRP2010 also noted that finding operating funds for “world observatories” like TMT and SKA¹⁷ is a challenge within current budgets for comparatively smaller facilities like Gemini. Clearly, operating funds must be considered in the context of the full portfolio of national projects.

As noted above, Gemini has changed dramatically in the years since LRP2010. Moreover, the Observatory is undergoing a strategic planning exercise to redefine its role in the 30 m telescope era. The results from this exercise will need to be known before the 2018 assessment point, when partners have to declare their intentions regarding Gemini involvement after the end of the International Agreement in 2021. As the result of this planning could be a radically different direction for the Observatory, it seems premature at this point to pronounce on the Observatory’s relevance to Canadian astronomy in 2022 and beyond. Alternatives between the current level of participation and full withdrawal should be considered, particularly considering that Gemini-South is the only optical/IR access Canadians have to southern skies, needed to effectively follow up on ALMA and SKA observations. We therefore reaffirm a modified version of the LRP recommendation:

Recommendation: The MTRP recommends that Canada’s participation in Gemini continue to be supported beyond the end of the 2016–21 International Agreement. The nature and level of that participation must be considered within the context of a coordinated plan for funding the operation of our ground-based facilities, together with any opportunities for broader access to the landscape of 8–10 m optical/IR telescopes.

5.2.3 JVLA and other NRAO facilities

As part of Canada’s close collaboration with the US National Radio Astronomy Observatory (NRAO) to enter the ALMA project via the North American Programme in Radio Astronomy (NAPRA), DRAO and NRC Herzberg designed and built the powerful WIDAR correlator for the Expanded Very Large Array (EVLA). The EVLA was renamed the Karl G. Jansky Very Large Array (VLA) upon the completion of the major upgrade in 2012; the lower frequency range of the VLA (which provides continuous frequency coverage from 1–50 GHz) overlaps with SKA1.

WIDAR began astronomical observations in 2010, and its most advanced modes are still being commissioned. Canadian astronomers were some of the earliest WIDAR users, participating in the Resident Shared Risk Observing (RSRO) program in which experts take up residence at NRAO to help commission new capabilities. Canadians have led next-generation radio continuum surveys with WIDAR, and have

made important contributions to the VLA Sky Survey (VLASS), a new all-sky centimetre-wavelength survey that will exploit the tremendous VLA sensitivity afforded by WIDAR. The VLASS team includes astronomers from seven different Canadian institutions, one of whom co-leads the project. Looking further into the future, Canadian astronomers are members of several working groups that will define the science case for the ambitious Next Generation VLA (ngVLA) project, a major proposed VLA upgrade that would bridge the frequency gap between ALMA and the SKA at the end of the next decade. Five years after WIDAR’s first light, the Canadian connection with the VLA remains strong.

The MTRP recognizes that SKA pathfinder science is being carried out by the Canadian community using a suite of radio facilities. A survey carried out by the AACS indicates that Canadians have experience using over a dozen single-dish and interferometric radio telescopes around the world at frequencies that overlap with the SKA1 range, and that over forty Canadian astronomers already envision themselves and their research teams working with SKA1 data in 2020. These data provide a benchmark that could be used to measure future growth. Canadian usage of NRAO’s Green Bank Telescope (GBT) is particularly significant, with over half of survey respondents reporting expertise using this facility. The GBT is the largest fully steerable dish in the world operating in a frequency range of 0.3–115 GHz in several observing bands; the GBT’s larger total collecting area, higher surface brightness sensitivity and broader frequency coverage is therefore highly complementary to the higher angular resolution provided by the VLA. Statistics compiled by NRC indicate that in the period from 2008–12, over 20% of all refereed journal articles resulting from GBT data included a Canadian co-author. It is worth noting that many of the key players in the WIDAR design and construction and the heaviest Canadian

¹⁷ We note that operation funds for both TMT and SKA will likely be needed before the end of construction, and the ramp-up and final operations cost of these facilities is not yet precisely known.

users of the VLA and the GBT are also those most actively involved in SKA precursor and SKA1 science and technology planning activities today.

The AACS usage statistics suggest that access to NRAO facilities is important to the research programs of a large fraction of the Canadian radio astronomy community. NRAO's long-standing open skies policy ensures that astronomers of all nationalities compete equally for observing time on its facilities. For the GBT, this open time is being whittled away as financial partners are sought to offset operations costs in response to the NSF Astronomy Portfolio Review of 2012. The current recompetition for the management of NRAO facilities, which treats the VLA and North American ALMA operations separately from the GBT and VLBI for the first time, adds an additional degree of uncertainty. In this context, the access to NRAO facilities guaranteed by NAPRA until 2018 provides security for Canadian radio astronomers whose programs depend on them. The strong collaboration between Canadian and NRAO astronomers on a variety of

current and future initiatives may provide a platform for extending the framework provided by NAPRA beyond this date.

5.2.4 CHIME

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) represents a new paradigm of radio telescope, relying heavily on computational power rather than expensive mechanical structures and cryogenic receivers. It was the highest priority medium-scale ground-based astronomy project recommended in the 2010 LRP:

The LRPP views CHIME as a key medium-scale experiment that could have high scientific yield at modest cost, and encourages the proposing team to vigorously pursue funding for this experiment. The LRPP endorses the project provided that a detailed study confirms its budget and the feasibility of its technical design and science goals.

After finalizing the detailed project concept, in 2012 the telescope and its core Cosmology backend received \$11M funding from the Canadian Foundation for Innovation (and partner provinces).

CHIME, see Figure 8, is a new radio interferometer located at the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, BC. It is the first major research telescope to be built on Canadian soil in more than 30 years and is now the largest telescope in continental North America with 2% more collecting area than the Green Bank telescope. Its core Cosmology target is to map the 21 cm emission of neutral Hydrogen from redshifts 0.8 to 2.5. The resultant three-dimensional map of hydrogen structure in the Universe will be the largest-volume survey ever made. It encompasses the critical period when Dark Energy begins to dominate the expansion of the Universe, allowing for a unique measurement of the expansion rate of the Universe through this critical epoch and constraining the Dark Energy equation of state in a way that is complementary to existing probes.



Figure 8. The telescope structure for CHIME, completed August 2015. The telescope consists of four parabolic cylinders 20 m wide and 100 m long with a focal length of 5 m. 256 dual-polarization antennas will be placed along the focal line of each cylinder and the signals are brought to a custom 2,048-input correlator. The instrument has no moving parts. Image from CASCA Cassiopeia newsletter – Autumn/Automne 2015

The CHIME telescope will also be a powerful instrument for detecting Fast Radio Bursts (FRBs), a relatively new, and as yet unexplained phenomenon that is perhaps the most exciting new radio astronomy development in decades. The excitement that today exists around transient radio science had not yet manifested when the project was proposed. However, research directions can move quickly when new technological capabilities enable new methods of probing the cosmos. In 2014 a new radio transient backend concept was developed for CHIME, allowing it to perform the high-cadence de-dispersion and the transient searches this science target requires. The FRB backend received \$5.5M funding from CFI and partners in 2015, making CHIME a dual-purpose experiment.

CHIME is also well suited for a variety of ancillary science objectives. It will produce an independent map of the intensity and polarization of the Milky Way visible from the northern hemisphere. CHIME can observe a very large number of known pulsars which pass through its beams each day, providing pulse arrival times that can be used for pulsar timing arrays.

Construction of the 8,000 square metre CHIME telescope structure was completed in August 2015 and the receiver electronics and custom correlator will be built and installed on site over the 2015/2016 winter. The CHIME correlator, consisting of custom Canadian-made digitizer/channelizer/networking electronics and a specialized massive array of graphics processor units (GPU) for spatial correlation, will be the largest radio correlator on earth when it comes on line in 2016, handling 2,048 channels with 400 MHz bandwidth. The 1.6 TB/s real-time data rate for CHIME exceeds the most recent (2014) estimate available from Cisco for global data rate to all mobile devices (~1 TB/s in January 2014) — the CHIME correlator could process the world's mobile data.

As the first generation of a new class of fast mapping radio telescopes, CHIME will simultaneously provide unique science capabilities and key technical insights. The demonstration of its novel techniques for cutting edge science will form the foundation for new telescopes and experiments that can revolutionize radio surveys requiring fast mapping speed, including high redshift 21 cm intensity mapping of the type that SKA-Low is targeting. In this manner, CHIME will act as a scientific and technical pathfinder for the SKA, pioneering the measurement of very low-surface brightness phenomena and developing key correlator hardware and calibration techniques.

The MTRP sees opportunity for Canadian astronomers to leverage the concepts and leadership that have been developed and investigate the application of CHIME-like techniques to future low-frequency radio astronomy facilities such as SKA-Low or Canadian-based initiatives addressing similar science.

The CHIME example highlights Canadian capabilities in technology, organization, leadership, and ideas. It demonstrates that this nation can take new Canadian ideas and build them into world-class Canadian-based facilities.

5.2.5 Single-dish submillimetre facilities

Although ALMA is a fantastically powerful and sensitive telescope, its field-of-view is set by the size of the 12 m antennas in the array, such that a single pointing with ALMA covers an approximately one arcminute of sky at 2.5 mm wavelengths. Larger fields can be observed by using a mosaic to stitch together many overlapping pointings, but the time required to cover a field of any significant size, even a single degree squared, rapidly becomes prohibitive.

As a result, there is a significant role for single-dish submillimetre telescopes in the ALMA era, particularly telescopes outfitted with wide-field continuum cameras at submillimetre wavelengths. The analogy at optical wavelengths is the synergy between wide-area surveys using MegaCam on CFHT to identify targets for follow-up spectroscopy with 8–10 m class telescopes. Thus, single-dish submillimetre telescopes serve a key complementary role to ALMA by providing rapid wide-field imaging and the capability for much larger surveys and samples than ALMA can reasonably achieve.

JCMT

Through NRC Herzberg, Canada was a 25% partner in the JCMT for over 25 years (the other partners were the United Kingdom and the Netherlands). The Netherlands withdrew from the JCMT partnership in 2013 and, as advised in LRP2010, Canada withdrew from the partnership in September 2014. Ownership of the JCMT was passed from the UK-STFC to the University of Hawaii in February 2015 and operation of the JCMT was taken over by the East Asian Observatory, a collaboration among observatories from China, Japan, Korea, and Taiwan. A consortium of UK universities obtained significant funding from STFC, which, along with funds contributed by the universities themselves, allows them to participate in JCMT operations at a significant level for three years. On the Canadian side, a consortium of six Canadian universities (Alberta, Lethbridge, McMaster, Saint Mary's, Waterloo, and Western) has raised a small amount of internal funding (approximately \$100k CAD/year) to allow continued Canadian participation in the JCMT for two years (2015 and 2016).

The scientific opportunities with the JCMT continue to be very exciting. Over-subscription rates at the first two calls for proposals in 2015 were very high (by a factor of nine for the small Canadian share of time). The JCMT recently com-

pleted a successful call for large observing proposals, with seven programs approved for close to 2,400 hours of observing time over the next two to three years. The scientific focus of the large proposals ranges from a search for protostellar transients at submillimetre wavelengths to the deepest 450 μm map of the high redshift universe ever attempted. Participation in the large programs is open to all Canadian astronomers in recognition of our years of contribution to JCMT operations.

The JCMT remains the largest single-dish submillimetre telescope in the world. Its continuum camera, SCUBA-2, is unsurpassed in its sensitivity and mapping speed while its heterodyne array receiver, HARP, continues to be very competitive. Although the telescopes in Chile (APEX, ASTE) and at the South Pole (SPT) are located at better sites, the JCMT continues to be the premier submillimetre telescope that is available as a general-purpose instrument to the broader astronomical community. In this way, the JCMT plays a complementary role to ALMA by providing the wide-field mapping capabilities that ALMA lacks. The JCMT consortium is continuing to recruit new partners and to solicit increased financial contributions from the existing partners as it seeks to position itself on a firm long-term financial and operational footing. Continued Canadian involvement in the JCMT would be a very useful complement to ALMA as well as serving as a bridge to new submillimetre facilities such as CCAT that are several years in the future. The MTRP commends the Canadian consortium for their efforts to secure Canadian access to the JCMT and encourages them to explore any opportunities that may arise to extend this participation further.

CCAT

CCAT is planned to be a 25 m diameter submillimetre-wavelength radio telescope. It will be built on Cerro Chajnantor approximately 600 m above the ALMA plateau. CCAT was ranked as a high pri-

ority for a new medium-scale project in the U.S. Decadal review in 2010. The 2010 LRP recommended that Canadian astronomers pursue participation in CCAT, including a thorough investigation of potential Canadian contributions. CCAT has enormous potential for panchromatic confusion-limited continuum surveys over tens to hundreds of square degrees, measuring the submillimetre spectral energy distributions of high redshift galaxies between 350 μm and 2 mm to obtain photometric redshifts and source luminosities, and unique capabilities for multi-line, multi-object spectroscopy at submillimetre wavelengths. A consortium of eight universities (Waterloo, British Columbia, Calgary, Dalhousie, McGill, McMaster, Toronto, and Western), became a founding partner in CCAT and currently participates in CCAT governance and planning. With its larger aperture and exquisite site, CCAT will greatly exceed the capabilities of current telescopes such as the JCMT in sensitivity, angular resolution, and mapping speed. CCAT's rapid mapping speed will be 22,000 times faster than ALMA at a wavelength of 350 μm . CCAT continues to generate a high level of interest among Canadian astronomers and would serve a key complementary role to ALMA by providing rapid wide-field imaging and the capability for much larger surveys and samples than can reasonably be achieved with ALMA.

LRP2010 as well as the 2010 U.S. decadal survey anticipated CCAT construction within this decade with operations beginning around 2020. However, the CCAT project has not progressed as quickly as anticipated. NSF funding has been markedly lower than assumed when the 2010 decadal survey was written, which meant the project could not be supported at the level initially envisaged (\$37M USD). Consequently, the project was directed to apply to the NSF Mid-Scale Innovations Program (MSIP) despite having been singled out as the top priority in medium scale facilities. A proposal was submitted in 2013; however, it was announced in late

June 2014 that the proposal would not be funded. Later that summer, Caltech withdrew from the CCAT partnership, resulting in a significant loss of staff and expertise. A Canadian proposal (by the eight founding universities plus Saint Mary's and Lethbridge) was submitted to CFI in June 2014, just days after the NSF announcement. Despite ranking high on science metrics, the CFI proposal was not funded. The primary criticisms were that not all construction funds were in place and that the route to obtaining operating funding was not clear.

The CCAT partnership currently includes Cornell University, the University of Colorado, the German universities of Bonn and Cologne, and the Canadian consortium of eight universities. Via its partner, AUI, CCAT owns the concession for the use of its 5,600 metre-high site for astronomy. There is growing interest by a Chilean consortium of industry, academia, and government in joining CCAT as a partner (i.e., contributing construction funds) rather than simply hosting the site, as well as indications that other new international partners may come on board. Discussions are also underway with NRAO as to whether they can contribute key management during the construction phase.

The telescope is being redesigned to reduce the cost of the project while keeping the sensitivity goals intact. Thus, the telescope will continue to be located at the originally chosen site and to have a diameter of 25 m. One decision has been to remove the enclosure (which was the largest of the contributions proposed originally for Canada) and to reduce the accuracy of the telescope's surface by not enabling active control of the surface at first light. These changes will make it more difficult for CCAT to operate in the very challenging 200 μm wavelength window. The design of the telescope itself will be simplified to a Cassegrain design, with room for only two instruments to be mounted at a time, and the surface will not need to be as accurate. One option being considered is

to build a smaller dish initially (10–15 m) on a larger mount that can be expanded to 25 m as funds become available. Overall, the descoping is designed to impact primarily operational aspects of CCAT and will result in slower overall survey speeds; however, no specific science case will be eliminated. The total cost for the descoped 25 m facility will be approximately 80% that originally proposed.

The next few years will be critical for the ultimate success of the CCAT project. With the withdrawal of Caltech and the ongoing re-arrangement of the partnership, there may be opportunities for Canada to take the lead on one of the first generation instruments, such as the multi-object spectrograph. There may also be a role for

Canadian companies in contributing to the construction of the telescope structure, most likely as a sub-contractor to one of the two companies submitting the overall design bids. Options that keep key scientific, technical, and engineering work in Canadian companies and universities are more desirable than sending money abroad.

Thus, because of its high scientific promise and its complementarity to ALMA, the MTRP recommends as follows:

Recommendation: *The MTRP reaffirms the importance of next generation single-dish sub-mm facilities, and recommends that Canadian astronomers continue to pursue participation in CCAT, subject to the project meeting its original science goals. Construction contributions that keep key scientific, technical, and/or engineering work in Canadian companies and universities will provide the most return on investment.*

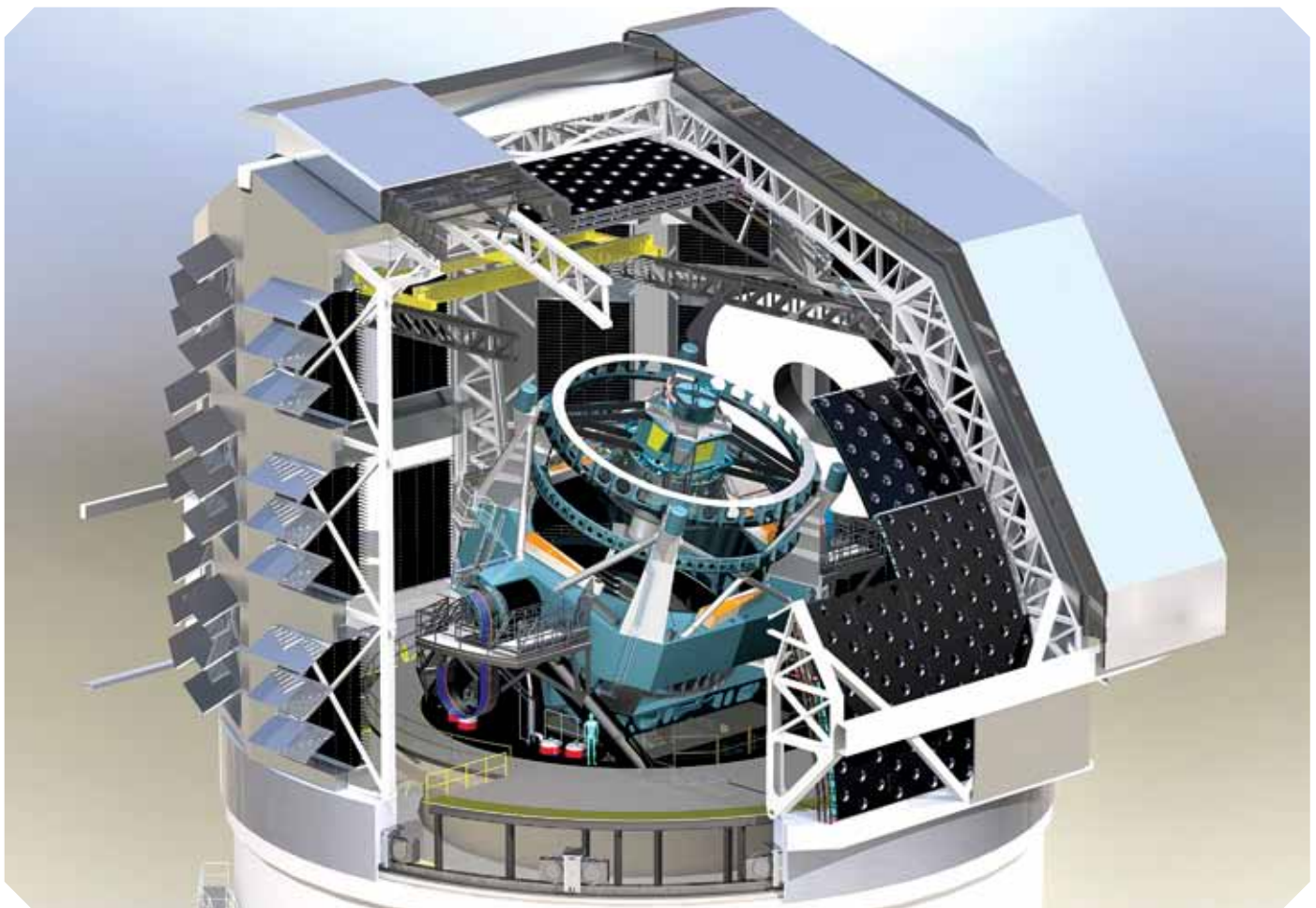


Figure 9. Cut-away image of the LSST dome and telescope. Credit: lsst.org

5.2.6 LSST

The highest-ranked large ground-based telescope in the 2010 US Decadal Survey is the Large Synoptic Survey Telescope (LSST), a dedicated survey instrument with an effective aperture of 6.7 m and a camera with a 9.6 deg² field of view (Figure 9). This telescope, which is now under construction on Cerro Pachón in the Chilean Andes, addresses a wide variety of scientific topics of interest to the Canadian astronomical community, including but not limited to the distribution of both near and distant asteroids in our Solar System, the structure of the Milky Way galaxy, searches for transients and variable stars, the evolution of galaxies, and cosmology probes using strong and weak lensing, large-scale structure, and supernovae. While this is a US-led project, the LSST Consortium has been actively soliciting involvement by international partners, who would contribute to operations in exchange for access to the data in a timely way. A university partnership centered at the University of Toronto has now joined as such an international partner; supporting ten PI slots (total cost \$2M USD, to be spread over the ten years of operations of LSST). There is also strong interest in a broader Canadian involvement.

There is a long history of major imaging surveys in Canada, especially with the CFHT, and the LSST represents a natural extension of those efforts. The LSST data are also highly complementary to MSE

as a wide-field spectroscopic survey, as well as more specialized surveys such as CHIME, and space-based surveys such as WFIRST and CASTOR.

The LSST survey will start in 2022, and will produce several tens of petabytes (1,016 bytes) in its ten years of operations. Gemini and TMT will be ideal telescopes for doing detailed follow-up studies of discoveries made with LSST. The project represents fundamental challenges in data processing, distribution, and scientific analysis, and has thus attracted the attention of the “Big Data” community. It also has a major education and public outreach component: the data can be used in classrooms across Canada to allow schoolchildren to learn astronomy and to take part in real Citizen Science projects.

5.2.7 Arctic

Arctic astronomy, and the potential for finding accessible sites that are cold and dry with long periods of darkness, continues to hold the community’s interest. At the time of LRP2010, initial measurements of image quality on Ellesmere Island, situated at 80° N latitude, had been taken and were suggestive of potentially superb image quality, equivalent to Antarctica Dome C without the problematic boundary layer. It was clear during the writing of LRP2010 that the image quality at this location is significantly better than any other site in Canada.

Follow-up site testing campaigns were conducted in 2011–12 using DIMM and MASS instrumentation on top of the Polar Environment Atmospheric Research Laboratory (PEARL), 15 km from Eureka. Analysis of these measurements yielded image quality comparable to Maunakea and Cerro Tololo in Chile. However, the PEARL location, building design, and a lack of sampling over an entire winter means that these image quality estimates are still only preliminary. Sampling for an entire winter away from the building on a tower platform would provide conclusive measurements, although at present, no plans exist to continue to monitor or develop Arctic sites.

Science motivation for using polar sites extends beyond image quality alone. One of the notable possibilities is monitoring of transient phenomena, such as exoplanet transits. For example, researchers from the University of Toronto ran a project monitoring 500 square degrees for two years from PEARL, which has now evolved into an NSF funded project to examine 10,000 square degrees from the US mainland and Antarctica. The inherent coldness of telescopes in the Arctic also has advantages for near infrared spectroscopy.

6 Space-based missions

6.1 General comments on strategic planning for space astronomy

Participation in JWST is a major achievement in Canadian space astronomy, generating enormous interest within the scientific community, whilst simultaneously being the most complex and costly enterprise yet attempted. As a result of engineering this ambitious, but successful, contribution to an \$8B mission, the technological and management capabilities of Canadian space contractors, as well as the aspirations of Canadian scientists, have grown hand-in-hand. As was highlighted in LRP2010, the potential of Canadian space astronomy, both in terms of science leadership and industry expertise, has reached the point where leading a mid-level space astronomy mission would be a bold, achievable and ground-breaking new step.

At present, the decision-making process by which missions are chosen has a number of inputs that are potentially opposing. As always, the astronomy community is prepared to help in any way it can to streamline this process and to aid transparency within the scientific and government spheres.

The CSA currently relies upon input from the JCSA, the LRP process, and its own newly-contracted “topical teams”. The topical teams-effectively discipline working groups-are tasked to produce the most focussed science cases for their particular science area within space astronomy. At a broader level, the JCSA, which has a long history within the community, has worked tirelessly to advise CSA and CASCA on opportunities and priorities in space astronomy. Lastly, the LRP and the associated MTR suggest missions, in the broadest and

most widely-considered sense, but are significantly detached from the detailed decision making process that leads to space-based missions being chosen.

The topical teams, and the preceding discipline working groups, add a level of detail beyond that present in the LRP process because the LRP view is extremely broad. As such, the topical teams are a welcome and potentially useful addition to planning that could aid both the CSA and the LRP process. The key issue is assuring topical team results are prepared ahead of an LRP, or MTR. Conducting topical team studies while developing an LRP or MTR, introduces a number of problems both in coordination and relative effort.

Despite these concerns, the overall goals for space astronomy of CASCA and the CSA remain the same: selecting the best missions and opportunities, both from a scientific and technology perspective, and then supporting them as effectively as possible. Thus, the MTRP suggests that future CSA topical teams be started 18 months ahead of the LRP or MTR reports. At the same time, it is also possible that the committee structures involved in the LRP process could be changed to reflect discipline areas rather than facilities. However, this would represent a significant change in the organization of the LRP process.

Recommendation: *The JCSA should work with CASCA and the CSA, to determine a precise input process for mission selection in space astronomy that is both transparent and equitable.*

6.2 Wide field Optical/IR Surveys from Space

The LRP2010 noted that the study of Dark Energy is a priority for Canada, and that both the US community (through the Astro2010 process) and ESA identified Dark Energy satellite missions as their top priority for space. The Euclid (ESA) and the Wide Field InfraRed Space Telescope (WFIRST; NASA/DOE) missions address this need for those communities. In light of this, LRP2010 made the following recommendation:

The LRPP recommends that Canadian astronomers participate in a major wide-field Dark Energy satellite mission. Joining Euclid or WFIRST as a significant partner would fulfill this recommendation, provided that we can (i) negotiate a partnership in the leading mission, and (ii) identify a contribution to the satellite instrumentation. Alternatively, a Canadian Space Telescope (CST) could be developed as a component of a Dark Energy experiment.

Since that time, and despite considerable effort on the part of the CSA and the Canadian astronomy community, the opportunity to participate directly in Euclid in a significant way has vanished. There remains the possibility of contributing ground-based imaging with CFHT through a Large Program, in return for some scientific participation within the large Euclid consortium. But with no opportunity to contribute directly to satellite instrumentation, no arrangement of this type will satisfy the LRP2010 recommendation. Two viable options remain: WFIRST and CST (now CASTOR). Though both have the potential to satisfy the recommendation, they are very different missions.

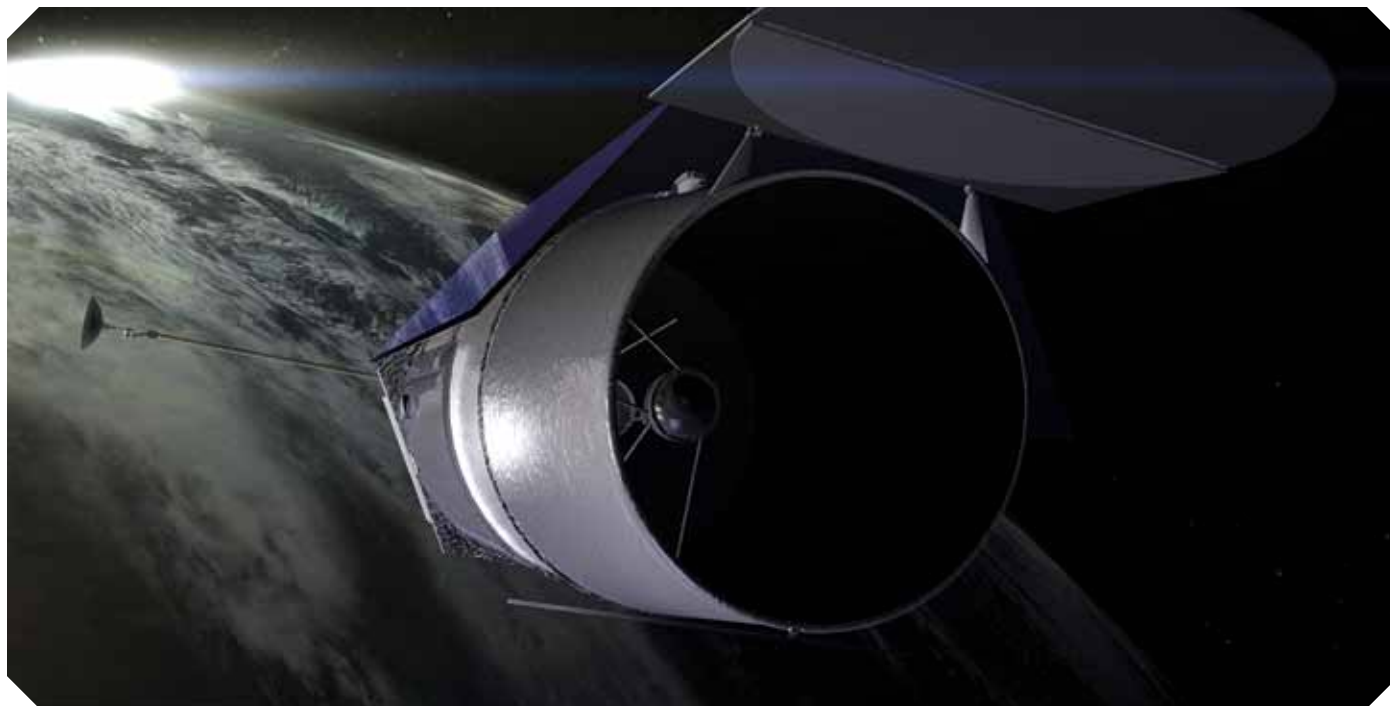


Figure 10. Visualization of WFIRST in orbit. While the mirror is a similar size to the Hubble Space Telescope, the images it takes will have 200 times the coverage of Hubble's Wide Field Camera. Credit: NASA Goddard/CI Lab

6.2.1 WFIRST

There is an opportunity, currently being pursued and defined by the CSA, to join the WFIRST project. WFIRST has evolved considerably since LRP2010 and since Astro2010 (US). It is now a larger, 2.4 m telescope, donated by the National Reconnaissance Office (Figure 10). This increase over the original 1.5 m design yields improvements in sensitivity and image quality, though with a smaller field of view. The possible addition of a coronagraph with designed contrast of $< 10^{-9}$ will allow imaging and integral-field spectroscopy of Neptune-mass planets in reflected light. Compared with Euclid, WFIRST will cover a smaller field but to significantly deeper limits with smaller PSF, in the near infrared, and with more passes. It has dedicated supernovae and exoplanet programs that do not exist with Euclid. Finally, while Euclid offers no Guest Observer (GO) time, 25% or more of WFIRST time will be used for a GO program. WFIRST is therefore considerably broader than a

dark energy mission, and that makes it of interest to a great number of Canadian astronomers. In particular it plays directly to Canadian strengths in supernovae, weak lensing and exoplanets, as well as wide field survey science.

Over the past year, more than 50 Canadian astronomy faculty have expressed interest in being directly involved in WFIRST. Dr. Mike Hudson from the University of Waterloo served as the Canadian representative on the Science Definition Team from December 2013, until its termination in 2015. Among his activities on this team, he conducted an informal survey of the Canadian astronomical community regarding their interest in participating in the WFIRST Science Investigation Teams (SITs). The response was very positive, with 42 people, including a significant fraction of all senior, active Canadian astronomers, registering interests distributed across all the SITs. In addition, there was a good response to a CSA Request for Informa-

tion at the end of 2014, for a "pool of experts" to assist CSA in independent reviews of concept studies for potential contributions to WFIRST hardware. Six prominent astronomers were named to this group, with acknowledgement from CSA that ad hoc contributions on specific issues might later be requested from others who responded to the RFI.

Following this, CSA initiated two concurrent concept studies for potential contributions: one on the Wide Field Imager (WFI), led by COMDEV (Ottawa), and another on the coronagraph, led by ABB (Quebec). The results of these studies were well received by NASA, which is actively following up. The CSA is to be commended for leading this work.

NASA has put WFIRST on an accelerated development path, officially launching the project ahead of schedule thanks to a large boost in funding from Congress. It is thus imperative to further define how Canada might engage in this project. One of the

challenges to fulfilling the LRPP recommendation will be to enable participation in such an ambitious mission at a sufficiently significant level. Participation at the level of ~5%, equivalent to our share in JWST, would be in line with the LRP recommendation for a \$100M investment.

Scientific involvement in WFIRST mission development is through the six SITs, comprising 174 members, who were selected in December 2015. While there are six participants on these SITs from the Canadian community, these all have “Collaborator” status, rather than the more influential “Co-I” status. While US Co-Is have access to substantial funding from NASA, others must provide proof of their own external funding. Without comparable funding, the Canadian community participation will be limited to a secondary role in scientific development, regardless of the level of hardware contribution.

We therefore make the following recommendation:

***Recommendation:** The MTRP reaffirms the exciting opportunity presented by WFIRST and its broad appeal to the Canadian community. In order to fulfil the LRPP recommendation we recommend that Canada begin negotiations to secure a significant (~5%) level of participation, at the earliest opportunity, so as to match NASA’s accelerated schedule. This should include contributions to critical instrumentation that, preferentially, is synergistic with Canadian science interests, and funded participation on Science Investigation Teams for a representative number of Canadian scientists.*

6.2.2 CASTOR

LRP2010 recommended that an alternative option to joining a NASA or ESA-led mission would be to develop a Canadian Space Telescope mission as a component to a Dark Energy experiment. This evolved from an idea generated at the 2006 Canadian Space Astronomy Workshop (CSAW), for a flagship mission focusing on wide-field UV/optical imaging and/or spectroscopy. It was further developed within CSA Discipline Working Groups from 2007–09. Now named the Cosmological Advanced Survey Telescope for Optical and uv Research (CASTOR), a concept study was launched in 2012, followed in 2013 by a two year Space Technologies Development Program study to retire a key source of technical risk: UV detectors and coatings. This study identified a need to review detector layout and optical design in order to mitigate red leak issues, and to re-optimize overall observing strategy.

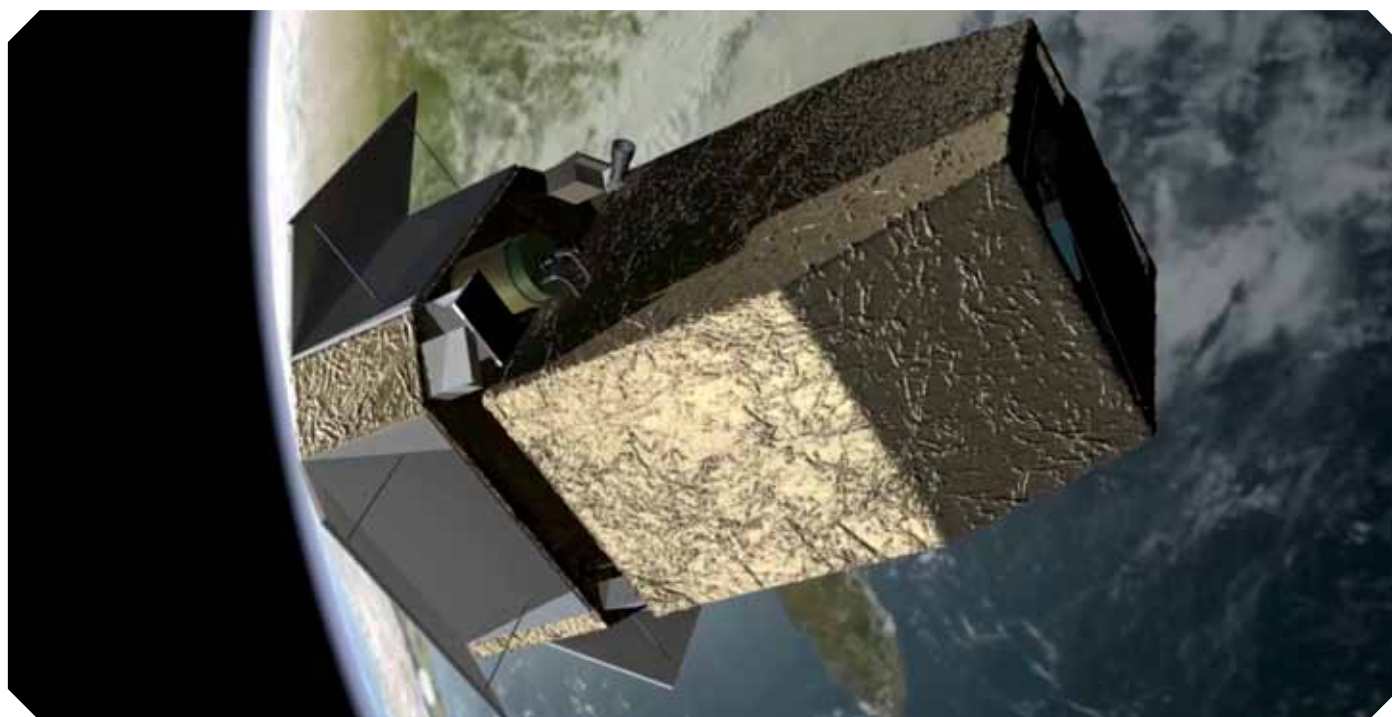


Figure 11 Rendering of the CASTOR telescope design. Credit: P. Cote

CASTOR contributes to dark energy exploration by providing the UV/blue spectral energy distribution coverage needed by both WFIRST and Euclid for accurate photometric redshift measurements. It is also complementary to LSST, providing access to the UV and generally improved sensitivity at wavelengths below 400 nm, together with the much higher angular resolution needed to overcome potential biases at faint magnitudes where LSST becomes confusion limited. It thus has significant strategic value for Canadians involved in these other projects. It is an exciting project in its own right, with a compelling science case that plays to Canadian expertise in wide-field optical imaging. In addition to its contribution to dark energy investigation, the surveys and GO programs executed by CASTOR will allow transformative research in the fields of galaxy evolution, near-field cosmology, stellar astrophysics and the outer solar system – all areas of strength within the Canadian community.

The project is well aligned with Canada's Space Policy Framework; in particular, it has the potential to become a high profile mission producing exceptional scientific results, as well as being a flagship for Canadian industry and the CSA. More than twenty companies have been identified, across Canada, who might participate in the design, development, and fabrication of mission components. As noted in the LRP, CASTOR would provide "the ideal opportunity for high-tech Canadian companies to showcase their capabilities", particularly in the areas of optoelectronics, high-volume data transmission technologies, X-band phased array transceivers, data handling units, memory boards, readout systems and control software.

The related detector study has identified and tested components for a focal plane array that significantly exceed specifications, and place Canadian technology in a world-leading position for this type of mission. If a full phase 0 study is not done soon, we support further work that

updates the optical design science case as a result of the detector study.

Members of the international community, particularly in France, India, Taiwan, Australia, Switzerland, and the US, have expressed interest in the CASTOR concept. The need for a replacement to, and upgrade of, the capabilities of HST for UV imaging is widely acknowledged, and other related mission concepts (e.g. Messier, CoWeX, HDST) are being developed. Without formal CSA support and an accurate cost estimate, it is difficult or impossible to develop connections with the necessary international partners. Regardless of what happens with Euclid or WFIRST, therefore, it is necessary to continue developing the CASTOR concept with a Phase 0 study, to identify the needs and technical requirements to allow a realistic assessment of the project feasibility, cost, and development plans.

Recommendation: *The MTRP strongly recommends that the CSA launch a Phase 0 study for CASTOR, with study results required within 12 months, so that this compelling project can be developed, presented, and competed in the international community. The LRPIC and JCSA should review the outcome of that study and make further recommendations as appropriate, well in advance of LRP2020.*

6.3 Cosmic Microwave Background Polarization Missions

Canadians have played key roles in nearly every important CMB result to appear

in the past 25 years. Clearly our biggest impact has been in terms of expertise and know-how that has contributed to advances in theory, data analysis, experiment design, and technology. The latter provides a concrete example. Essentially every competitive CMB polarization experiment that is presently operating on the ground or on stratospheric balloon platforms is using Canadian-built technology to read out their transition edge sensor (TES) detectors. This includes leading experiments such as the Atacama Cosmology Telescope and BICEP, which use readout electronics designed and built at UBC, and the South Pole Telescope and POLARBEAR, which use readout electronics designed and built at McGill. Likewise, two stratospheric balloon missions have flown CMB polarimeters recently: Spider and EBEX use the UBC and McGill technology respectively, demonstrating these systems in a space-like environment. Canadian-built readout electronics, as well as software and analysis expertise, have become a requisite for successful experiments.

Since the 2010 LRP was released, technological developments and new measurements have resulted in tremendous progress for teams attempting to indirectly detect gravity waves emitted from an early period of inflation using the Cosmic Microwave Background (CMB) polarization. The field has matured from its infancy to one of the most-watched fields in cosmology (and indeed in physics).

At large angular scales, the B-mode polarization component of the primordial CMB is expected to be dominated by inflationary-epoch gravity waves. At smaller angular scales, secondary-effects due to gravitational lensing imprint a signal in the B-mode component that traces structure. This generates a guaranteed signal which is extremely sensitive to the physics of dark energy and the details of the neutrino sector.

The first detection of B-mode polarization at small angular scales due to gravitational

lensing was made with the South Pole Telescope (the discovery paper had a Canadian first author, despite being from an American led collaboration) and proved the maturity of the instrumentation and analysis techniques. This was rapidly followed by a detection of large angular scale B-mode polarization with BICEP2 in March 2014 (with significant Canadian co-authorship) — the signal that, if it originated in the CMB, would be the hallmark of inflation-ary gravity waves. The scientific world was stunned by the potential implications.

However, there is now general agreement that, although the measurement appears correct, the origin of this B-mode polarization is more likely from dust emission in our galaxy, rather than a feature in the CMB. This emphasizes the need for sensitive observations covering a large number of frequency bands, many of which are only accessible from satellite platforms. The excitement that accompanied the result highlights the global interest in this as perhaps the most powerful modern-day probe of very early universe physics.

Definitive measurements of B-mode polarization in the CMB will ultimately be made from satellite platforms, as has been the case for the temperature anisotropies. International collaborations designing and building satellite CMB polarimetry observatories have expressed interest in using Canadian technology for these instruments. The Canadian Space Agency has recognized this signature Canadian technology and invested in creating higher technical readiness level (TRL) prototypes with funding through its Science and Technology Development and the Flights for the Advancement of Science and Technology (FAST) programs, readying it as a potential mission critical contribution to a satellite mission.

Recently, LiteBIRD (Figure 12), a high profile JAXA-led international mission planned for launch in 2022, has been funded in Japan for phase A1 (as a Strategic Large Mission) and received new

funding in the US for its implementation concept study phase as a mission of opportunity from NASA. LiteBIRD employs a kilo-pixel superconducting detector array spanning a dozen frequency bands on a cryogenically cooled 100 mK focal plane, with an optical system at a temperature of 4 K. It will have an angular resolution of 30 arcminutes at 150 GHz. In both the Japanese and American proposals, Canadian readout electronics were presented as the baseline technology for the mission.

LiteBIRD is not alone in the CMB polarization landscape. A novel concept, called PIXIE, is being explored in the US. PIXIE uses Fourier transform spectroscopy and multi-moded optics to measure both the polarization anisotropy and probe spectral distortions. The PIXIE team is likely to re-propose for the next NASA MidEx opportunity in 2016 or 2017. The team has strong Canadian participation.

In Europe, several CMB polarization concepts have been proposed. Although none have been successful to date, there is strong community support for leadership or participation in a CMB polarization mission to follow on the success of Planck.

A dedicated CMB polarization satellite will be a large international partnership. With support from the Canadian Space Agency, Canadian researchers are uniquely positioned to play an international leadership role in this mission, partnering with one or more other agencies to make the definitive measurement of large to medium angular scale CMB polarization.

Recommendation: *The MTRP recognizes the unique role that Canada could play in an international CMB polarization satellite mission. The MTRP strongly recommends that the CSA engage in discussions with its sister agencies for a hardware and science role in a new mission such as LiteBIRD or other mission opportunity such as PIXIE that may arise in the immediate future.*

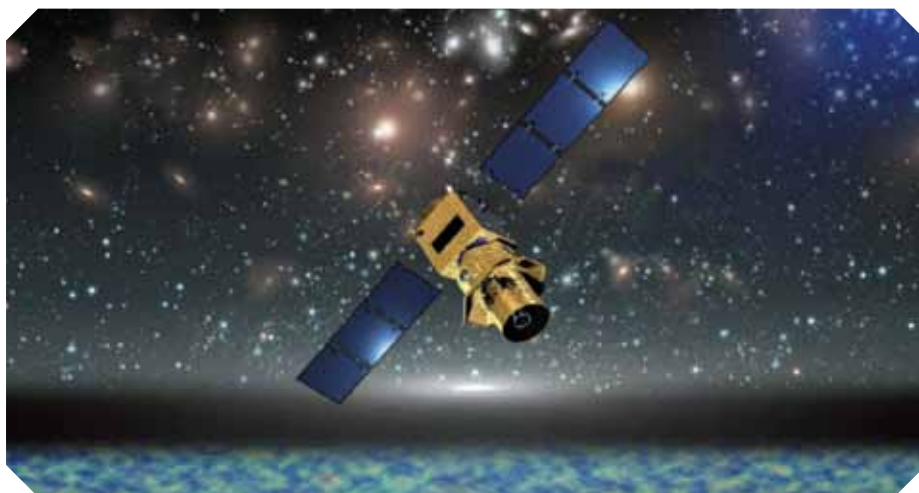


Figure 12 Artist's impression of the LiteBIRD mission that is designed to measure the signature imprinted on the Cosmic Microwave Background polarization by gravity waves emitted from a period of inflation a fraction of a second after the Big Bang. Canadian technology forms the baseline readout for the project. Credit: NASA MO Proposal, UC Berkeley

6.4 Athena

Involvement in the next flagship high-energy astrophysics (HEA) mission was ranked as the highest medium-scale space opportunity in LRP2010. This recommendation recognized the general importance of probing matter both in its most common state (hot gas in galaxy clusters) and in its most extreme – and hence often most physically revealing – conditions. Such investigations include extremes of gravity (black holes), density, magnetic field (neutron stars), temperature (supernova remnants), and speed

(jets, gamma-ray bursts). The selection of IXO also reflected the growing number of Canadian astronomers working in these fields, and the importance of multiwavelength astronomy.

In LRP2010, the specific recommendation read,

The LRPP strongly recommends Canadian R&D involvement in the International X-ray Observatory (IXO) as its number-one medium-scale space priority. This is because of its excel-

lent foreseen scientific capabilities that will be a superb match for the expertise of the Canadian HEA community, but also with an eye toward capitalizing on technical expertise gained from fabrication, implementation, and calibration of the ASTRO-H metrology system. Involvement with IXO is consistent with CSA's mandate of growing experience and capability.

IXO was a worldwide project which was also ranked as the highest space-based priority in the US decadal survey. Its aim

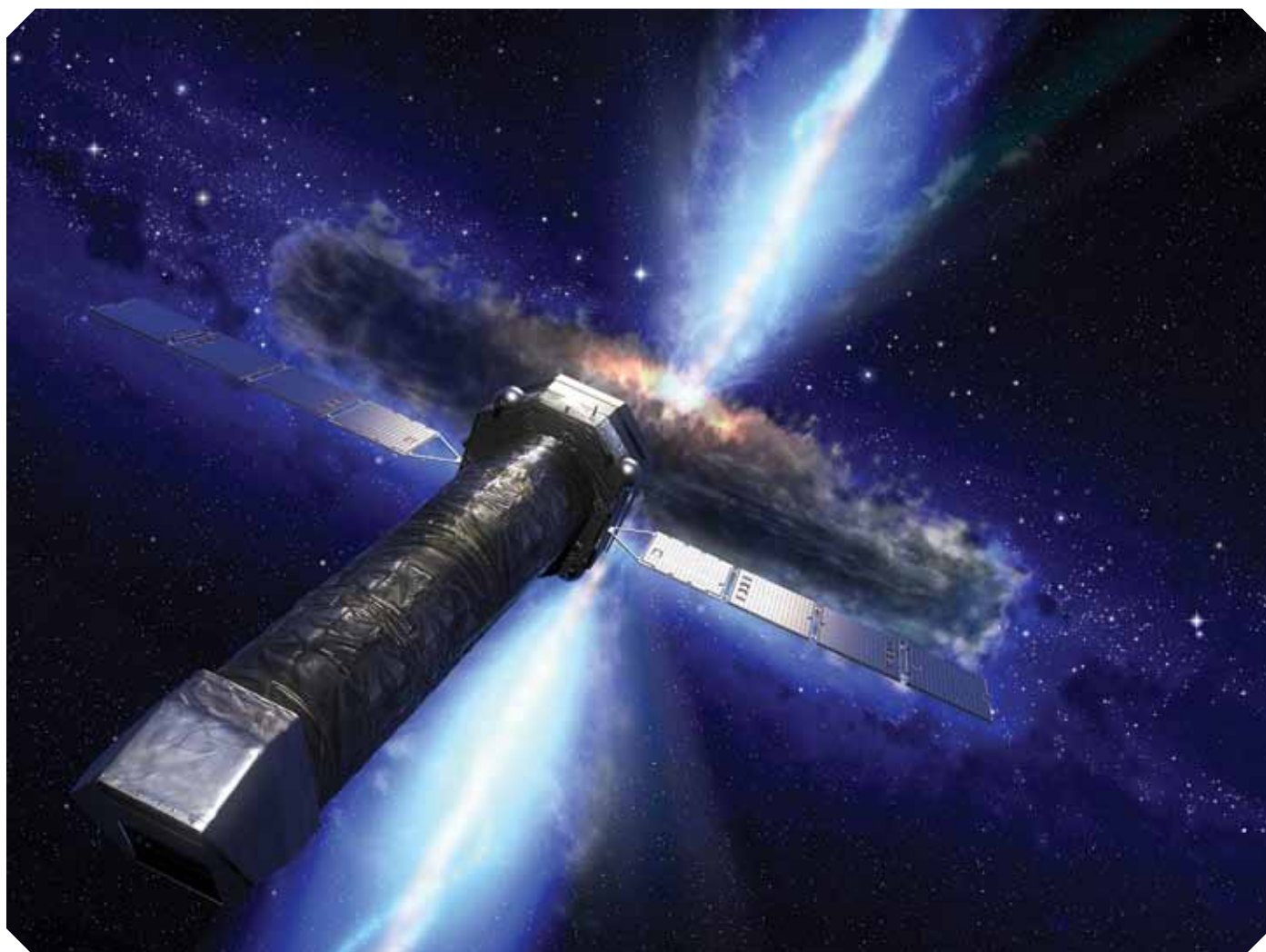


Figure 13. Athena is planned to survey a violent Universe of exploding stars, black holes and hot gas. New silicone pore optics will provide improved resolution and an enlarged collection area compared to current X-ray missions. Credit: ESA

was to significantly improve on existing missions in all facets of survey speed, collecting area, spectral resolution, and energy coverage. The project, however, ended up being considered overly ambitious and risky, and in the US, budget constraints forced the wavelength coverage to narrow to optical survey instruments. This led ESA to turn to a more focussed and robust European-led X-ray mission, the Advanced Telescope for High-ENergy Astrophysics (ATHENA, now written Athena; approved for development for a nominal 2028 launch). While the mission cost has come down from that anticipated for IXO, Athena is still budgeted at approximately €1.4B, or over \$2B CAD, assuming a €1 to 1.5 CAD exchange rate.

While less ambitious than IXO, Athena will still be transformational in the same sense that ALMA has been compared to previous millimetre arrays, and that TMT will be compared to 10 m class telescopes. Athena will provide well over an order-of-magnitude improvement in effective area, field of view, and/or spectral resolution over previous missions as well as missions planned for the nearer future. Two instruments are proposed for the mission, an X-ray integral field unit, covering a five arcminute field with high spectral resolution in the energy range 0.2–10 keV, and a 40 arcminute wide-field imager with a similar energy coverage but less spectral resolution. The revolutionary use of silicon pore optics will enable the unique combination of a large collecting area and good angular resolution. The two instruments also work in a complementary fashion: wide-field imaging allowing rapid mapping of the sky to reveal populations such as high redshift black holes, while the integral field unit is capable of studying the precise phenomenology of hot gas to learn, for example, how it accretes and evolves in dark matter halos. All these advances make Athena the “world observatory” for X-ray astronomy, and it will make advances across many field of HEA.

Building upon the ASTRO-H mission and successful contribution of the Canadian ASTRO-H Metrology System (CAMS), Athena is a natural aspiration for involvement for the HEA community, and associated technology development, in Canada. As was highlighted in detail within LRP2010, this community has grown extensively since 2000, to now contain close to 30 faculty and almost 100 individuals in total. Four current Canada Research Chairs exist in this field, and there are also former chair holders as well. Further, despite lacking individual scientists who work directly on X-ray instrumentation, the successful delivery of CAMS to JAXA in 2015 has also demonstrated that the community is capable of working effectively with industry partners who possess the necessary instrumentation expertise. At the same time, development of flight qualified readout electronics for transition edge sensors (TES) has been funded. Taking all factors together, the overall size, success, and technological expertise of the HEA community has continued to grow since 2010.

As for other research specialities, access to leading facilities is essential to maintaining competitiveness and attracting top talent. With Athena viewed as the “world observatory” X-ray facility, not being involved would be a significant blow both to the current community and the potential for attracting the next generation of researchers. Similar arguments can be made on the technology development side, where involvement in designing and building major new hardware would provide a venue to train engineers and develop new technology-related skills.

For all Athena’s promise as a ground-breaking facility, the route to participation is unclear. Aside from the previously mentioned metrology and readout electronics for the calorimeter imager, Canada has expertise in satellite pointing and calibration support. However, a more significant challenge is the overall size of the contribution required to participate in the mission. There are indications that

partnership will be open only to agencies contributing a significant piece of the mission. Despite launch being scheduled for 2028, the project is moving ahead swiftly, and we need to continue our involvement.

Recommendation: *The MTRP recommends that Canada continue to explore the possibility of contributing to the science instrumentation on Athena, as well as the cost and the access to the mission that would be gained from such a contribution.*

6.5 SPICA

SPICA is a planned far-infrared space mission led by Japan with participation from ESA. In its original concept, SPICA would have been 100 times more sensitive than Herschel because of its cooled primary mirror. Canadian participation was made even more interesting because of the potential to leverage our expertise in Fourier Transform Spectroscopy (FTS) technology. LRP2010 gave Canadian participation in SPICA very high priority under medium-scale space projects.

SPICA has undergone considerable revision in the past five years. The size of the primary mirror has been decreased somewhat to 2.5 m (Herschel was 3.5 m) and is now based on the design for the Planck telescope. One side effect of the smaller mirror is that an FTS would no longer be the best instrument for spectroscopic surveys, particularly in the $z=1-3$ redshift range. A dispersive system based on a diffraction grating is needed, but this provides only low resolution spectroscopy ($R \sim 300$). A complementary high-resolution component is needed and this is likely to be provided using a Fabry-Perot interferometer.



Figure 14. The BIT telescope about to be launched from Timmins, Ontario in September 2015. Credit: Steven Li

There is still the potential for Canada to remain a key player in the mission, possibly by taking on the Fabry-Perot development. The design of the Fabry-Perot involves metrology and a cryogenic mechanism and is not so different from the scanning mechanism used for an FTS, which builds on our heritage from Herschel and JWST. Thus, SPICA still has immense potential and there is a potential route for Canada to be involved.

SPICA had a successful Mission Design Review by JAXA in summer 2015. Funding for SPICA will be submitted to the ESA M5 call expected in early 2016. If funded, launch would be in 2029 or 2030.

Recommendation: *The MTRP recommends that Canada explore the possibility of contributing elements of the Fabry-Perot instrument to SPICA, as well as the cost and the access to the mission that would be gained from such a contribution.*

6.6 Small payload and balloon-borne missions

Canada has continued to build expertise in using small satellites and balloon-borne instruments for astronomy, which are funded by the CSA through grants. The BRITE Constellation is the first project to use nanosatellites for astronomical measurements – aiming to better understand the structure of the most luminous stars. With balloons, BLASTpol is being used to study the early stages of star formation, while EBEX and SPIDER aim to find direct evidence for the epoch of inflation in the cosmic microwave background.

An issue identified in LRP2010 was that funding opportunities for small satellite missions were perceived as unclear. Indeed, this was one reason that, of the six nano-satellites that comprise BRITE Constellation, the two Canadian ones were launched several months after the first launches by the partner countries Austria and Poland. This was despite the fact that the project was conceived in Canada and that the satellites were designed (and mostly built) at the University of Toronto Institute for Aerospace Studies (UTIAS).

Since that time, the Canadian Space Agency has introduced two programmes that have helped address these worries at the low-cost end: the regular Flight for Advancement of Science and Technologies (FAST, up to ~\$500K) opportunities, and a new balloon program, joint with the French space agency (CNES) called STRATOS (\$0.5M–\$2M), with launches from Timmins (ON) as well as other CNES sites. Both programs have been used by the astronomical community, with a nice example being the recent test flight of the Balloon-borne Imaging Telescope (BIT, see Figure 14), which allowed the team to prove the ability to point a half-metre optical telescope sufficiently well to obtain diffraction-limited and thus high-resolution imaging. With that successful test passed, the path is now open for a longer flight (aimed at measuring the masses of clusters of galaxies using weak lensing) as well as for constructing a larger successor, SuperBIT, which aims to obtaining high-resolution, wide field optical images of large parts of the sky, thus providing an early preview of the type of science aimed for by Euclid, WFIRST and CASTOR.

At present, the Timmins flights have weight and duration restrictions which limit their appeal for astronomy science flights – indeed, for BIT's longer science flight, the team will rely on NASA launches and funding, while for SuperBIT the hope is to use one of the new class of super-pressure, long-duration balloons. It is hoped that by further collaborating with CNES, the payload restrictions on launches can be relaxed. This would open up astronomical opportunities more generally; e.g., the proposed high contrast planet imaging experiment MAPLE would likely similarly benefit from a less stringent weight limit and from longer duration flights.

On the funding side, the main element that is missing is a regular call for proposals for somewhat higher-cost small projects, at the few million dollar level (i.e., that required for, e.g., the construction and launch of a nano-satellite). Given the above concerns, the MTRP recommends as follows:

Recommendation: *The MTRP recommends that Canada continue to support small-scale exploratory satellite projects and balloon-borne missions through regular calls for proposals, and that the CSA introduce regular calls for proposals for nano- and microsatellite opportunities and contributions to instrumentation on larger missions, so that these types of projects can also proceed through a competitive funding process.*

6.7 Current and near-term space missions

6.7.1 JWST

JWST is an ambitious successor to the Hubble Space Telescope. With a 6.5 m mirror and a formidable instrument suite it is far more capable than HST and promises to be a transformative facility for many areas of research. Broadly, JWST is designed to address four fundamental science themes: “The End of the Dark Ages: First Light and Reionization”; “The Assembly of Galaxies”; “The Birth of Stars and Protoplanetary Systems”; and “The Origins of Life”. Optimized to operate at near- and mid-infrared wavelengths, it will have a tremendous synergy with the next generation of ground-based telescopes, including the TMT, which will be able to follow up spectroscopically the many new classes of objects discovered by JWST.

JWST was identified as the highest priority for space astronomy in LRP2000, and again in 2010. Canada secured a large contribution to this project (\$150M, 2.5% of the total cost) under CSA direction, representing our largest ever investment in astronomy, at that time, and still the largest investment in space-based astronomy. Through this investment Canadians are guaranteed at least 5% of the available observing time for our contribution of the Fine Guidance Sensor (FGS), which includes the guider itself as well as the Near-Infrared Imager and Slitless Spectrograph (NIRISS). Though the launch delay anticipated by LRP2010 came to pass, the current launch date of October 2018 has been stable for some time and appears secure. Integration of the various parts is of such public interest that the NASA Goddard cleanroom is broadcasting its activities via a webcam (Figure 15).

At the time of the LRP2010, the science module of the FGS was intended to be a Tunable Filter Imager (TFI). However, technical challenges to this instrument put the TFI at risk given the schedule constraints imposed by the JWST project. Thus, in 2011, the instrument was rescoped into NIRISS, a simpler but uniquely powerful instrument that can be configured for broadband imaging, multi-object low-resolution slitless spectroscopy, high-contrast imaging, and cross-dispersed spectroscopy optimized for exoplanet transit work. The FGS was delivered to NASA in July 2012, representing an enormously important milestone for which CSA and the FGS science team are applauded.

JWST far surpasses the HST in terms of its functionality; its instrument suite will include multi-object and integral field spectrographs, a slitless spectrometer, a non-redundant pupil mask, two coronagraphs, and three imagers. Much work remains to be done to ensure the Canadian community is ready to exploit these powerful instruments immediately upon launch, and to maximize the Canadian contribution to JWST science during its (minimum) five-year lifetime. The proposed six-month proprietary period adds additional time pressure for science teams to exploit their data before they become public. It is important that potential users are well informed and prepared in advance of the launch date, and funded workshops and help centres (which proved to be successful with ALMA) would help to achieve this.

As was emphasized in LRP2010, the operational model for JWST is challenging because observing time awards will not necessarily be synchronized with funding opportunities for using the data. This puts Canadians at a competitive disadvantage relative to US astronomers, who have opportunities to apply for funding associated with successful proposals.

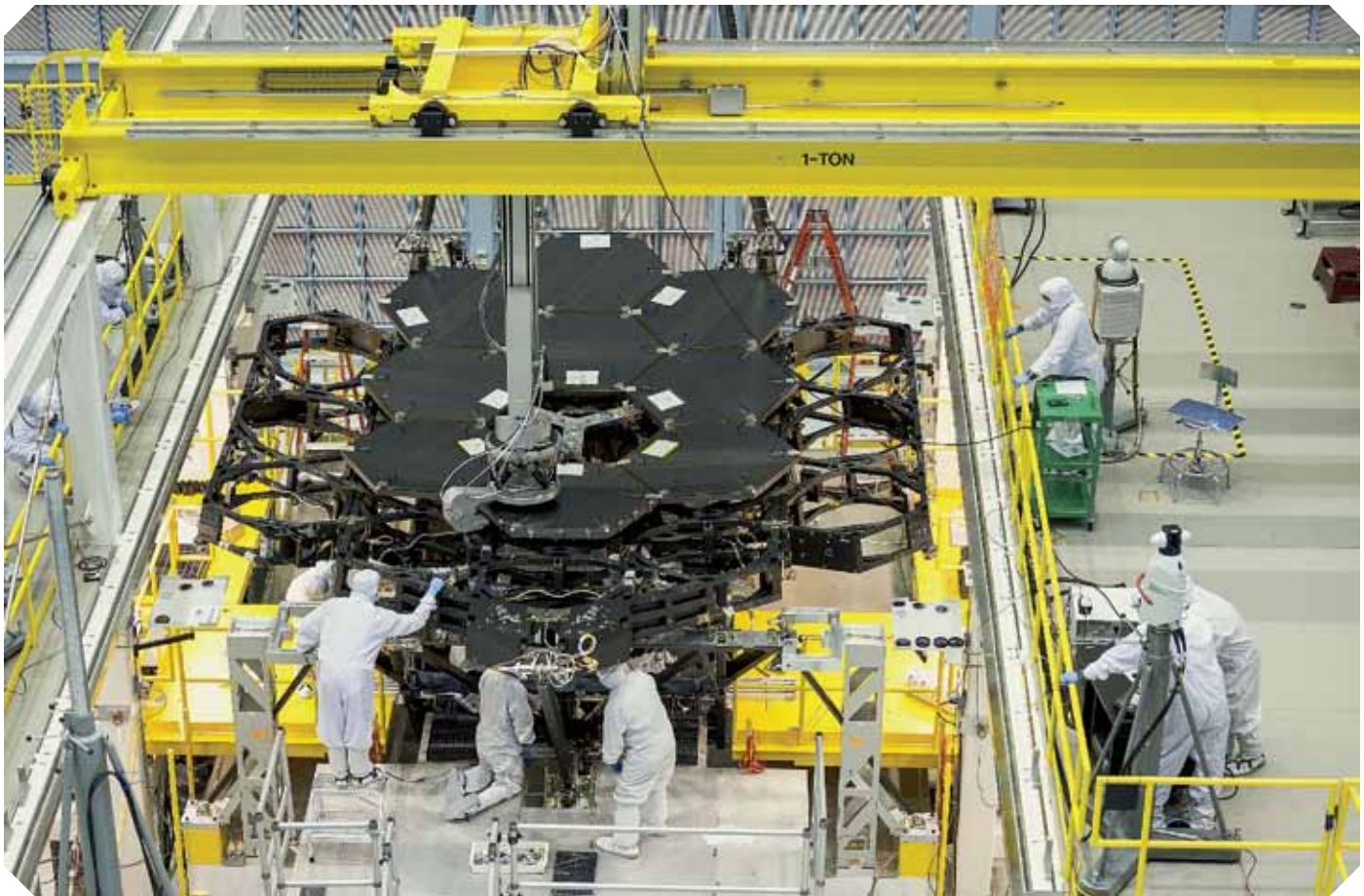


Figure 15 The JWST mirror segments being integrated on to the mirror support structure at NASA Goddard Space Flight Center. Credit: NASA Goddard/Chris Gunn

In support of these concerns LRP2010 recommended:

The LRPP recommends that CSA set aside funds in the SSEP program to provide support for four PDFs in support of JWST and other CSA supported missions. This investment will help ensure that the exceptional data expected from these missions will be utilized to their full extent.

Indeed, the funding level required to support four PDFs per year, relative to our share of JWST time, is likely to be well

below what NASA will provide for US astronomers who are awarded observing time. Estimates for the per year support of JWST science in the US are between \$40M–\$60M USD, scaling down by the fraction of observing time available for each country, this is equivalent to a support in Canada of around \$2M–\$3M per year. To take full advantage of the 5% of observing time available to Canadian astronomers will require that financial support from all sources be competitive with what is available to our US colleagues.

Thus, the MTRP reaffirms the recommendation from LRP2010, as follows:

Recommendation: *The MTRP reaffirms the essential importance of continuing science support to exploit our investment in JWST as well as other CSA-supported missions. This should include funding workshops and help centres to enable the community to ramp up expertise prior to launch, as well as a mechanism for funding post-doctoral fellows to work on and with JWST data.*

6.7.2 Ultra-Violet Imaging Telescope on Astrosat

Astrosat comprises four X-ray telescopes as well as two telescopes covering ultraviolet and blue wavelengths, with all telescopes co-aligned and operating simultaneously, allowing studies with an unusually broad energy coverage, from the blue/ultraviolet to both soft and hard X-rays. Astrosat is an India-led mission, for which Canada provided the detectors and read-out electronics for the Ultra-Violet Imaging Telescopes (UVIT). Canada has a 5% share of the observing time.

Astrosat was launched on 28 September 2015, and first light with the X-ray instruments occurred on 12 October 2015. The ultraviolet telescopes were opened later, allowing for the instruments to be properly “outgassed,” with first light happening on 1 December 2015. So far, the results are excellent, with both satellite and instruments working nominally, and, in the case of UVIT, actually exceeding specifications.

Going forward to the operations phase, there will first be a period with guaranteed-time observations of pre-selected targets. In parallel, once this in-orbit

performance of all instruments has been properly characterized, there will be a first call for proposals, likely in March 2016, for observations starting in September 2016. Observations from all instruments may be proposed for observing, serving a very wide range of scientific interests. The Canadian Space Agency is funding an expert to support Canadian proposals and data processing for UVIT. We urge that the level of support be adequate to make optimal use of our share of this unique facility.



Figure 16 Visualization of ASTRO-H. CAMS will precisely measure any distortions in the boom alignment, allowing precise calibration of the hard X-ray detections. Credit: JAXA

6.7.3 ASTRO-H (Hitomi)

The ASTRO-H mission (Figure 16) is a continuation of a series of innovative X-ray satellites led by Japan. It is noteworthy in two aspects. The first is the unique ability to precisely measure the energies of incoming X-ray photons, which allows, for example, accurate separation of emission from different elements in hot plasmas. The latter in turn, allows for a range in studies, from measurements of the yields of those elements produced in superno-

vae to constraints on the dark matter in clusters of galaxies from the properties and velocities of their hot gas. The second noteworthy aspect is the ability to focus high-energy X-rays, using multi-layer, grazing-incidence mirrors. These novel mirrors give much improved angular resolution and a much reduced background (and thus improved sensitivity).

Canada's contribution is tied to the second aspect: it provides the metrology required to position the grazing incidence

mirrors accurately, some dozen metres in front of the detectors. In exchange for our contribution, Canadian astronomers are allowed to apply for time within the JAXA block of observing time, and also, arguably more importantly, get to provide input into the planning process.

ASTRO-H launched successfully on February 17, 2016 and was renamed "Hitomi."

7 Computing, networks and data

7.1 Overview

Computing and networks are now a key component in improving productivity across numerous spheres of society. In astronomy research, it has long been the case that computers are as necessary as telescopes. Indeed, in a recent survey conducted by the CASCA Computation and Data Committee (CDC), 65% of CASCA members reported that it was likely they would need access to the significant computing resources provided by Compute Canada (CC) in the next five years. Essentially all new telescope facility designs incorporate data processing and reduction as key step in the development process, and for some (the SKA is a notable example) it can have a fundamental influence on the overall capability. Overall, ICT infrastructure is a critical factor in the overall success of research astronomy.

LRP2010 highlighted that hardware investments were falling significantly behind other countries, and recommended increasing investment in computing to \$50M/year, a doubling of the net investment from 2005–10. At the same time, the report noted that CC would need to support additional new services, particularly cloud computing and recommended that the organization move in this direction. The last recommendation made focused on developing a coherent Canadian Data Management Policy that focused on end-to-end management of data, especially for the needs of upcoming “world observatories”.

In the five years since LRP2010 was authored, cloud computing concepts and the growth of data analytics, commonly falling under the “Big Data” banner, have undergone an almost exponential growth in visibility. Astronomy, as a field, has been a pioneer in data management and analysis, so adaptation to these trends has happened quite naturally. While the

perceived promise and actual returns on research in this area still exhibit a gap, the influence of new techniques and approaches has filtered through to the point that graduate courses are being constructed with these tools in mind. Indeed, many astronomy graduates are finding employment in the growing field of data science where their skills are directly applicable.

In terms of the overall management and distribution of computing and networks, the federated governance remains the same as it was in 2010. Networking is addressed at the federal level by CANARIE, at the provincial level by the optical regional advanced networks (ORANs), and last mile connectivity is the domain of the research institutions. Funding of CANARIE is assured for the next few years with the commitment of \$105M for the 2015–20 period, while ORAN funding is more sporadic and reflective of individual provincial government initiatives. Computing infrastructure continues to be provided by provincial and CFI-funded consortia under the banner of CC.

There have been some key changes in the organization of CC, with a consolidation of sites resulting from the decommissioning of aging equipment and only four new sites being funded in the 2015 Cyberinfrastructure competition. However, CFI has also allocated new funding streams to directly address software development, which is a welcome addition. The 2015 Economic Action Plan for Canada also announced a new CFI commitment to digital infrastructure, interpreted as computing and data infrastructure, of \$100M. Adding matching funds means there is a significant reinvestment potential, although years of below-G8 average investments in computing infrastructure (as detailed in LRP2010) mean that Canada has a long way to go to be seen as internationally competitive.

Data management issues have also evolved significantly in the last five years. With the rise of CANFAR as the key directing body for data support in Canadian astronomy, an increasing number of researchers are participating on its Science Management steering committee. Through this committee an informal approach to policy on data management is evolving, although nothing official is established. As a critical part of CANFAR, the CADC has invested significant resources in moving analysis services over to a cloud-based model operated largely on CC hardware. This creates potential benefits in terms of scalability, but has also highlighted challenges in the deployment of this kind of infrastructure: insufficient capacity and a lack of desired hardware configurations within CC (although future hardware purchases by CC could address this issue). However, the CADC is acutely aware of archive access/security and, if needs be, will maintain a separate copy of data on proprietary hardware.

7.2 Compute and storage resources

CC will celebrate its tenth anniversary in 2016. In that decade there has been significant evolution in its management structure, from a bottom-up federated approach in early days, to the centralized structure that operates today. Despite a number of teething troubles, the organization is finally reaching some level of maturity, and processes, such as resource allocation, are now well established and comparatively optimized, even if compute resources are insufficient. There remain concerns about storage allocation procedures and tailoring of proposals to machine architecture, but many of these issues can, at least in principle, be addressed.

At the same time that the new structure of CC was put in place, a number of consortia essentially centralized coordination to provide more streamlined representation at both the provincial and federal level. The regional consortia interests are now represented by WestGrid, Compute Ontario, Calcul Quebec, and ACEnet. These organizations continue to be one of the strongest voices for users, the base of which has grown by a factor of two in just five years to over 10,000 across the country.

Despite the extensive changes in the CC structure with the goal of improving the overall efficiency of the organization, hardware funding for the 2010–15 period was lower than anticipated in LRP2010. With astronomy being a significant user (approximately 5% of cycles are used by 350 astronomers who constitute only 0.5% of the CC user base) research aspirations have been notably impacted. Additionally, from an operational perspective, inefficient and old hardware has been operated beyond its cost-effective life-cycle, and the comparative expense of this led to CC proposing, in 2015, to defund a number of hardware installations. Although having a staged roll-out over two years, the implementation of this strategy will lead to a reduction in the number of sites with supported hardware from 23 to 11.

As part of the SPARC consultations conducted by CC, CASCA's CDC conducted a review of projections for computing requirements in Canada in the 2015–20 time frame and submitted a white paper outlining these findings. Overall computing requirements were estimated as growing by a factor of 10x, while average storage requirements were estimated to grow by a factor of 3x, although a number of projects, most notably the SKA, would have vast storage requirements. Astronomers placed a high priority on building large-scale computational and storage facilities to support simulation, data analysis and mining. Funds for software development were also acknowledged as necessary.

System Name	Location	System parameters
LP	University of Toronto	66,000 CPU cores, 15 PB of storage
GP1	University of Victoria	8,500 CPU cores, 7 PB of storage
GP2	Simon Fraser University	25,500 CPU cores, 20 PB, 192 GPU cards
GP3	University of Waterloo	26,500 CPU cores, 20.5 PB, 64 GPU cards

Table of new systems funded as a result of the 2015 CFI Cyberinfrastructure competition. These systems will be operated by regional consortia.

Additional input was provided to CC by other fields, as well as commentary from the Advisory Council on Research. Overall predictions, weighted by usage, led to CC estimating an increase of 7x for compute needs and a 15x increase in data requirements by 2020. These findings were included as motivating factors in the CC proposal for four new systems (see table) that was submitted, and funded, as part of the 2015 CFI Cyberinfrastructure competition. While originally budgeted at \$15M, CFI upgraded this award to \$30M. In addition, as part of the additional \$100M investment in Cyberinfrastructure from the Economic Action Plan, another block of \$25M has been released to the CFI, of which \$20M will go to hardware, making the net CFI hardware investment for 2015–17 \$50M. A further \$25M will go towards software development over the same time span.

The remaining \$75M of the \$100M Economic Action Plan investment announced in 2015 will be spent in the 2017–20 time frame. Assuming a split of \$50M towards hardware and \$25M towards further software development, the total hardware investment by CFI over the 2015–20 time frame should be close to \$100M. After full match from

provinces and vendors, this is an average per year investment of \$50M, which corresponds exactly to the recommendation made in LRP2010. Based upon numbers presented therein, the resulting investment would place Canada in the middle of the G8 on an HPC investment as a function of GDP basis; although it is worth emphasizing expenditures in other countries have likely increased. Additionally some installations, most notably the US “Blue Waters” installation, which cost over \$200M USD, is not listed on the Top 500. While computing requirements are growing across many subject fields, this increase in funding is obviously extremely welcome but is unlikely to significantly change Canada's overall position given the extended period of underfunding. Machines in the Top 20 already have 100,000+ CPU cores today, so the LP system will not meet the “Tier 1” desire that many researchers have stated. Future funding is needed to address this.

The MTRP commends both the government and CC in moving to address and fund the replacement of ageing compute infrastructure and the progression of supporting new computing paradigms, most notably cloud computing. However, as many distributed research projects (of

which CANFAR is a notable example) move towards software-as-a-service approaches there will be a need both for further hardware investment and the provision of new services beyond computation and software.

Recommendation: CC provide services such as authentication/authorization, and efficient distributed storage platforms that encompass both archiving and user spaces in a scalable way. Services like this will enable the development of increasingly sophisticated analysis platforms.

7.3 Evolution of the Management of Digital Research Infrastructure in Canada

Before discussing the CADC and CANFAR, it is also important to note that the increase in the public perception of the importance of digital infrastructure has led to the evolution of new policy bodies above both CC and CANARIE. Virtualization of computation, combined with the increased sharing of data, makes the digital landscape considerably more complex than in the era of batch jobs and remote file transfer protocols. In recognition of this changing landscape, the Leadership Council on Digital Infrastructure brought together representatives from universities, CANARIE, CC, Canadian Research Knowledge Network, Research Data Canada, Canadian Association of Research Libraries and the granting councils along with Industry Canada representatives. However, the large number of stakeholders and the complicated nature

of digital research infrastructure makes policy direction difficult to determine from a bottom-up process, not only due to the difficulty of coordinating stakeholder interests but also in terms of managing technical issues, including standards.

Nonetheless, two summits led to the formulation of a number of recommendations by the Leadership Council and arguably had a role in the increased investment in digital infrastructure that is now occurring. However, simultaneously, Industry Canada has conducted its own consultation process on digital research infrastructure which ended in September 2015. CC made a significant contribution to this process and, perhaps critically, has emphasized the importance of technical advice within policy and decision making processes. Their submission includes a suggestion to formally create a Digital Research Infrastructure Advisory Council with both policy and technical elements to provide direct advice to the government.

7.4 CADC and CANFAR

For over two decades the CADC has been a critical component of the astronomy research infrastructure in Canada. The evolution of the CADC has been well-documented elsewhere, but key statistics for 2014 include: 20 staff, over 400 Canadian users, 7,000 (international) registered users and 91 million file requests to the 2.3 PB archive. This highlights both the international nature of astronomy and the data-driven nature of the field.

But the key evolution for the CADC in the last five years is the emergence of the CANFAR cloud-based platform for both serving and analyzing observational data. While the CADC originally grew out of NRC requirements to provide researchers with data, CANFAR evolved primarily on the needs of university researchers to perform analysis on data. The recognition that an encompassing platform can be

built has seen the rise of a close collaboration between the CADC and the CANFAR steering committee which primarily comprises university-based researchers. Recognizing the importance of careful data management, and the growing need for analysis, the HAL report stressed:

“CANFAR is thus a critical evolution in Canada’s astronomy computing environment that will allow researchers to take advantage of the opportunities afforded by this new global reality.”

Development of the CANFAR platform has been strongly aided by a series of NEP awards from CANARIE. Despite a number of successes in the past five years (indeed since 2011 over 500 publications cite CANFAR support), two key issues have co-developed: the need to transition on to hardware supported by CC (as part of the wider government hardware rationalization policy) and the vision of extending the capabilities of the platform to encompass additional analysis and visualization methods, particularly the analysis of simulated data. Combining simulated data with observational analysis pipelines allows the creation of forecasts for observations (commonly called “mock” observations) rapidly and more importantly, accurately, by directly matching observational procedures. Such augmentation must be done in a flexible and scalable way, which is non-trivial.

Thus, the transition and augmentation of this innovative platform requires significant investment. However, there are delicate political issues as CADC staff are NRC employees and a number of federal agencies have distinct rules on passing funding to other federal agencies (notably CFI). A proposal by the CANFAR consortium to the CFI Cyberinfrastructure fund was rejected on these grounds, despite CANARIE funding precedents and the majority of the funding going to non-NRC personnel. Such rulings, appear to be distinctly against the spirit of

the 2011 “*Innovation Canada: A Call to Action*” report, led by Mr. Tom Jenkins, which highlighted the importance of a close working relationships between the NRC, universities and industry. Funding problems, induced by structural governance issues, have the potential to severely impact science progress.

Recommendation: *Given the increasingly blurred relationship between data and analysis products, the MTRP recommends that the Agency Committee for Canadian Astronomy (ACCA) meet to discuss possible strategies to avoid policy traps that preclude the funding of the development of critical and innovative software infrastructure for CANFAR.*

8 Governance, Funding and Budgets

8.1 The complexity of the ground-based astronomy governance landscape

First we reiterate what is meant by “governance” in the context of astronomy in Canada and this MTR report, since astronomical research by its nature cannot be “governed.” There are two primary contexts relevant to the MTR in which the term “governance” is applied. The first is the development and operations management of national and international observatory facilities to which access is provided on a competitive basis for Canadian astronomers. Such facilities include, for example, CFHT, Gemini, and ALMA. The second context relates to grants and contract funds to conduct research with these and other facilities.

The investigation carried out by the Hickling, Arthurs, Low Company concluded:

“Governance of astronomy in Canada is remarkably complex, owing in large part to the fact that there is no central structure for allocating funding for big science projects. Instead, the community must mobilize and align both funders and performers to ensure that, in an environment of limited resources, Canada can continue to partake in what are increasingly expensive international astronomy projects.”

“While the astronomy community is one of the most organized research communities in Canada in terms of setting priorities and engaging stakeholders in a strategic dialogue

on future investments, its governance process is challenged in several respects. One is the high level of uncertainty over future facilities, all of which depend on multi-governmental funding partnerships. At any given time, there are a number of major next-generation telescope projects being proposed by various international coalitions of scientists, many of which are in competition with one another for government support.

“This uncertainty is compounded by the fast pace of evolution in the field. Driven partly by new technological advances, new opportunities are developing faster than can be planned for by the current decadal planning process. Another challenge is the fact that investments in major new facilities typically require new money beyond the funding envelopes of the agencies that support astronomy.

“Finally, the effectiveness of this governance arrangement is also challenged by the degree of informality and associated lack of clarity of the roles of participants.”

This “challenge” was also highlighted in LRP2010 and little has changed since, so a more effective and efficient form of governance of astronomy in Canada is still desirable. One change that partially addresses the rapidly evolving landscape in astronomy and related technologies was the implementation of the LRPIC that proved, for example, extremely useful in updating and reaffirming the LRP priorities during the process to fund TMT.

The MTRP commends the LRPIC for the exceptional job it has done over the past five years and sees it as a valuable and continuing addition to the LRP process.

Yet, the challenges involved in negotiating a share in TMT clearly demonstrate why the overall governance of astronomy in Canada needs improvement. The process played out over a number of years and involved CASCA, ACURA, a coalition of representatives of industry and academia, NRC, and of course, the astronomy community.

In fact, there was very little “process” – it was quite ad hoc and changed in response to evolving situations. Both from the perspective of the community and funding agencies, the process would have been better facilitated if there had been a central body that was clearly recognized by all stakeholders as representing the interests of the entire community, while being respected in a policy advice role.¹⁸ This central body would oversee the development of a coherent, strategic plan for astronomy and be able to respond to requests from the government or other organizations about priorities. One possibility to consider might be to utilize the proposed NRC Herzberg Advisory Board, discussed below, for this purpose. Another possibility might be for ACURA to evolve to take on this role. However, serious consideration should also be given to the possibility that astronomy in Canada might be better served by an entirely new national organization.

While the MTRP approves and applauds the directions and actions taken by NRC Herzberg to date, the evolving roles and responsibilities of NRC within the restructured federal government is another rea-

¹⁸ The Coalition for Canadian Astronomy fulfilled some of this role during the TMT era but, as a small committee formed by mutual agreement of the three organizations involved, it is not an ideal candidate to play an expanded long-term role.

son for considering the formation of a new national organization. NRC is becoming more and more like any other department that responds primarily to industrial priorities rather than acting like a traditional research council, and NRC Herzberg now stands out even more as an anomaly.

Internally, NRC Herzberg takes its direction and priorities from the LRP, folded together with ongoing commitments for the operations of Canadian facilities. This mission, together with the ability to work with the Canadian community to develop long-term strategic plans, is under threat within the new federal government structure. The Herzberg Advisory Board, largely composed of representatives from academia and industry, was disbanded several years ago so now there is no ongoing external review of performance or assistance in establishing short term and long-term priorities and objectives. The MTRP heard that Herzberg Astrophysics staff as well as the broader community would welcome the re-establishment of the Herzberg Advisory Board. Another disadvantage of the current system is that, as a government department, NRC Herzberg cannot lobby or very effectively promote the interests of astronomy in Canada. An entirely new national organization would be able to do this most effectively, but even the least significant of the changes suggested here, namely the reinstatement of an Advisory Board, can represent community interests to the government more effectively. However, perhaps more importantly, the wide representation of stakeholders in either of these possibilities would ensure they would be recognized as more broadly representative of the community as a whole.

In the short term, at minimum, we recommend that an external Advisory Board to NRC Herzberg be formed, that includes both senior representatives of academia (e.g., at VP Research level) and relevant industries across Canada. This Board should

be capable of making recommendations on strategic issues in astronomy, consistent with the overall priorities of Canadian astronomers as embodied in the LRP.

Recommendation: An NRC Herzberg Advisory Board, constituted of senior representatives of academia, including both administrators and scientists, as well as industrial representatives, should be established to advise on the portfolio and programs of NRC Herzberg.

As discussed, over the longer term, to address both the lack of direct formal community guidance to NRC Herzberg and the lack of a central body that represents the interests of the entire Canadian community, the formation of a new separate national organization¹⁹ could be considered to provide guidance to the government. Astronomy in Canada might be better served by a TRIUMF-like model for NRC Herzberg rather than remaining as just a “portfolio” of NRC. Indeed a number of possible management scenarios were outlined in LRP2010, including government owned, contractor-operated possibilities, wherein the contractor represents community interests. In this case, there would automatically be extensive community involvement.

Concerns over strategic decision-making for “Big Science” facilities have been voiced across multiple fields, and astronomy is especially distinct, given the fundamental role the NRC plays in the operation of government observatories primarily for university-based researchers. In this regard, the ACCA has previously been a highly useful vehicle for establishing interagency collaboration, and there are current issues that it could meet to address (page 58).

Further, international collaborations, facilities and the science they undertake, will all become increasingly complex. Navigating this mixture of policy and science, even domestically, is a challenge without well-framed procedures. A proper process of decision making and policy setting for “Big Science” in Canada is sorely needed.

8.2 Funding

8.2.1 Overall funding

The HAL report gives a brief summary of the overall Canadian funding for astronomy:

“In 2009, Canadian astronomy received some \$86 million in support, most of which (~83%) is directed towards infrastructure. NRC-HIA and CSA are the largest funders, accounting for 80% of total expenditures, almost all of which is for the development and operation of facilities. With this support, Canadian astronomers have been able to directly access 10 facilities since 1990, totaling approximately \$175 million in investments.

“By most measures, however, these investments are below the average of Canada’s peer group of countries. As a percent of gross domestic product (GDP), five countries – the United Kingdom (UK), Italy, France, Germany and the United States (US), – spend at least twice that of Canada. In operations support alone, these same countries spend four times that of Canada.”

¹⁹ ACURA might be such an organization but, at least at present, is primarily concerned with the promotion of, and participation in, TMT and SKA and so lacks breadth. A description of ACURA activities is given in more detail in the fall 2015 issue of Cassiopeia.

There is some optimism that this may be changing. On April 6, 2015 the Canadian government announced²⁰ that it would provide \$243.5M funding for TMT over the next decade, joining the US, Japan, China and India who had already committed funding. The Canadian money will mostly be spent by industries in Canada who will provide the iconic enclosure and a state-of-the-art adaptive optics system. Naturally, this announcement was heralded throughout the astronomical community with great excitement – the scientific promise of TMT is immense, in practically every branch of astronomy. Participating in TMT will also bring Canadian industries in contact with high tech counterparts in some of our most important trading partners. As mentioned in Section 4.2 Industry and Economic Impacts, thanks to the international, open nature of astronomy, it plays important roles in both strengthening innovation and the training of HQP.

However, as discussed in Section 8.1 The complexity of the ground-based astronomy governance landscape, the path towards successful funding of TMT was extremely complex and laborious, and appeared to most of those involved to be ad hoc at best. Also, since Canada lagged well behind the other partners in making a commitment to the project, its impact in the final design was lessened and Canada's reputation suffered. We reiterate that a more logical process for funding "Big Science" in Canada is still very much needed.

8.2.2 Update on astronomy funding since 2010

NSERC funding

One of our main findings and concerns is that the funding for astronomy that is the responsibility of NSERC has declined in the past five years since LRP2010 from a total of \$11.8M to \$11.0M. Instead, the

\$11.8M should have grown into \$12.8M to keep pace with inflation²¹ from 2010 to 2015. The average annual "Discovery Grant" per researcher has declined in 2010 dollars to \$34.1K when inflation is accounted for. This > 10% decline has had significant impacts on the abilities of several researchers to support their graduate students and maintain their research output.

Following political imperatives, NSERC recently established several new programs to fund more directed research and innovation. One of these is entitled "Idea to Innovation Grants" the objective being to "accelerate the pre-competitive development of promising technology originating from the university and college sector and promote its transfer to a new or established Canadian companies." Thus far, astronomy has not benefitted significantly from this program perhaps because, as described in the industry section (4.2 Industry and Economic Impacts), astronomers have already been doing this for a long time, so that many possibilities aren't "new." Another reason is that the funds have in general been directed towards other priorities (e.g., environment, health, etc.) rather than sciences like astronomy. However, the MTRP encourages Canadian astronomers to be more proactive in relating their research to practical innovations, and to make sure that successes are more broadly publicized.

NRC funding

The combined operational and capital budgets of NRC Herzberg Astronomy and Astrophysics have remained more or less flat over the past five years, although the annual contributions to offshore facilities have grown recently as a result of the decline in the Canadian dollar exchange rate. Any real long term trends in the NRC Herzberg budgets are difficult to assess in detail since there have been several major changes in accounting, and

in the organization of NRC within the federal government. Many administrative services were recently centralized either at NRC Ottawa or more broadly in the government as a whole (e.g., all computing services). Furthermore, the extra funding to support the Canadian contributions to ALMA/EVLA ended in 2009 and no major new projects were initiated. This, of course, will change when the funds for TMT begin to flow. By 2020, the LRP panel should have a much better indication of the direction of NRC support for astronomy in Canada.

CSA funding

The potential for funding new space-based facilities, even at the level of concept studies, has not evolved as expected in 2010. One of the highest priorities of LRP2010 was significant involvement in a major space based mission (EUCLID, WFIRST, or CASTOR) primarily to investigate dark energy, at a level around half that expended on JWST. This has not happened, largely because the CSA budget, whilst not appreciably shrinking, has been forced to cover cost overruns associated with the RADARSAT Constellation mission, that are estimated to be several hundred million dollars (precise figures are unknown at this time). When costs associated with JWST are removed, the annual budget associated with the remaining space missions averages just under \$7M (a summary of CSA annual budgets by mission, which excludes studies, is provided in Appendix C). It is clear that any significant aspirations for space astronomy requires the CSA budget for space astronomy to at least double, and funding Canadian-led missions clearly goes beyond the current funding envelope.

20 <http://www.cbc.ca/news/technology/canada-finally-commits-its-share-of-funds-for-thirty-meter-telescope-1.3022659>

21 <http://www.bankofcanada.ca/rates/related/inflation-calculator/>

CFI Funding

During the 2010–15 period, CFI continued to provide funding for astronomy projects at more or less the same rate (in the absence of inflation) as before. When matching funds are included, this averages ~\$6.4M per year, although competitions are not held every year. The major grants since LRP2010 include one in 2012 to CHIME (\$4.6M), another to upgrade CHIME for transient observations in 2015 (\$2.4M), and one to construct a copy of the SPIRou spectrograph for the southern hemisphere (\$4.5M). The total of all CFI grants for astronomy in the 2010–15 period was \$13.7M, equivalent to \$34.2M including matching funds.

CIFAR Funding

A sixth cycle of the Cosmology and Gravity program began in 2012, marking a remarkable fifth renewal, under the leadership of program Director Prof. J. Richard Bond. Overall funding levels remain as before, with contributions amounting to approximately \$1M per year, which goes towards the support, at least in part, of over 20 personnel across Canada. As outlined in LRP2010, the program has moved towards a closer relationship between theory and observation, encapsulating the founding philosophy of the program, and this progress has been further cemented recently with some members of CIFAR participating in the innovative CHIME experiment. Looking

to the future, another renewal of the program is clearly of great importance to the Canadian astrophysics community and the MTRP strongly supports this goal.

***Recommendation:** The MTRP reiterates the importance and value of the CIFAR Cosmology and Gravity program, which has been of exceptional benefit to Canadian astrophysics. The community is strongly encouraged to seek a further renewal of the program.*

9 Demographics

9.1 Introduction and Trends

Using data collected by ACURA, LRP2010 highlighted significant growth in the Canadian astronomical community over the 2000–10 decade. Driven by a series of research successes (Canadian astronomy was ranked #1 in the world in a 2005 citation impact study by Thompson ISI), combined with the growing need for additional resources as aspirations rose, all cohorts from faculty numbers to undergraduates involved in research, grew at rates between four and nine percent per year. We also emphasize that astronomy is somewhat unusual in that a large fraction of the graduate students come from a physics undergraduate background, making undergraduate to graduate flow discussions appear counter-intuitive.

The survey was updated by ACURA in 2013 and rather than focusing on long term trends, which are broadly similar to 2010 data, we focus here on the nearer term 2007–13 period. As can be seen from Figure 17, which includes all years for completeness, all the cohorts continued to exhibit growth.

The total number of individuals engaged in astronomy research in Canada is now just over 860 people. Beginning with undergraduates participating in research, the growth in this sector has slowed to 3%, which is close to the overall growth rate of undergraduate physics and astronomy students suggested by CAUT data. The overall percentage of the undergraduate population participating in research is likely levelling off. However, the growth of faculty numbers is weakening relative to the growth in both the PDF and graduate student populations. Compounded growth rates show faculty numbers increased at about 2% per year, PDF numbers at almost 6% per year and graduate students

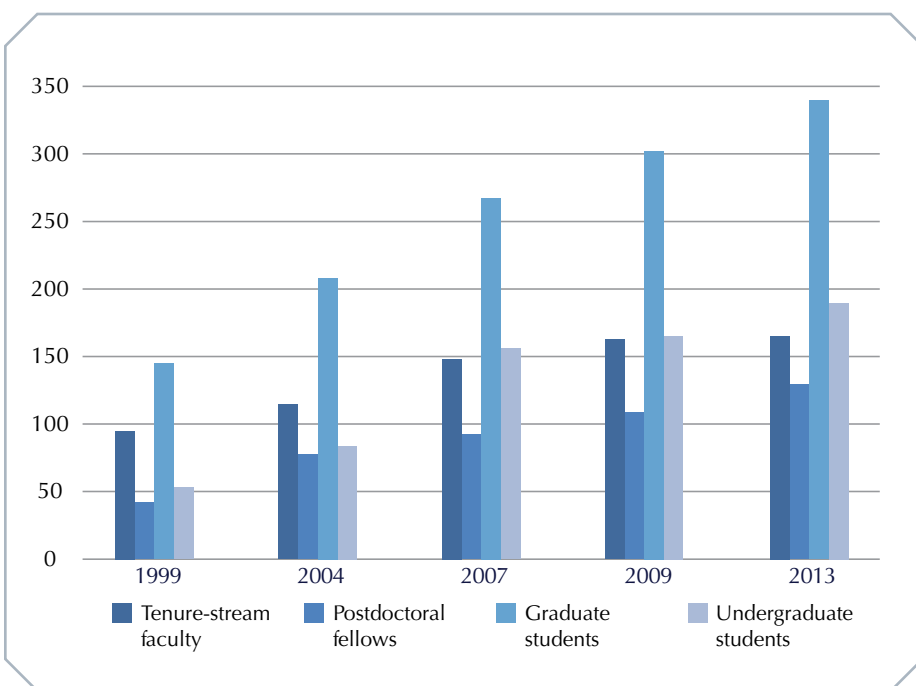


Figure 17. Time evolution of the sizes of the various cohorts in Canadian research astronomy.

at 4% per year. In six years this amounts to 17 new faculty positions, 37 new PDF positions, and 71 additional graduate students. Once the entire populations are considered, however, the faculty to graduate student ratio has been close to two since 2004. For comparison, the faculty to graduate student ratios in biology and chemistry are 3 and 2.5 respectively (CAUT data). Aside from overall research successes and productivity, increases in undergraduate enrolments (CAUT numbers suggest overall physics and astronomy enrolments have grown at 2–3% per annum) have provided economic motivations for both more graduate students and professors. Overall, the growth of astronomy in Canada appears to be sustainable from a demographic perspective.

While it is tempting to highlight a growing disparity between PDF and faculty posi-

tions, the current ratio in Canada is 0.8. Via an informal survey of other countries, it was noted in LRP2010 that the typical international PDF to faculty ratio is slightly over 1, and even with the increase in the ratio in the 2013 data, Canada remains below its competitors in this regard. PDFs remain a strong driver of research capability and are a key factor in the successful and rapid commissioning of facilities. Detailed arguments were made in LRP2010 about the significant impact the loss of the NSERC Special Research Opportunities (SRO) program had on Canadian astronomy. It was then proposed that facility-oriented PDF funding, with a value equivalent to that of the lost SRO funds, be put in place. As of the time of writing, these funds have not been approved. Hence, the MTRP reiterates the LRP2010 recommendation.

Recommendation: *The MTRP reiterates the key role that PDFs play in research capability and facility commissioning, and hence reaffirms the high importance of NSERC funding a postdoctoral program in support of Canada's access to major facilities.*

Canadian researchers have also become more productive in terms of research outputs and citation rates. Although year to year variations can be significant, broad trends suggest overall research output, measured in terms of paper outputs, has grown by almost 40% since 2007 with overall citation rates (measured on three-year baselines) growing at close to 50%. This more than surpasses the overall growth in the community size of 23%. International collaboration continues to be very strong in the field, with Canadian researchers publishing with colleagues from over 80 different countries. By any measure astronomy is an exceptionally international endeavour. Perhaps unsurprisingly, given geographic and historical ties, the US and UK remain the two countries most commonly collaborated with. It is worth noting that while collaboration with European countries remains very strong, Japan (10th), China (13th), and India (21st) are also already significant sources of collaborative interaction with Canadian researchers. In the next decade it is reasonable to anticipate further strengthening of these connections due to the TMT collaboration.

The overall “envelope” of NSERC funding to astronomy, over half of which is not Discovery Grant related, has fallen by approximately \$1.4M since 2007 (inflation adjusted), an 11% reduction. Most of this loss can be associated with MRS program

changes and reduced support of graduates and postdoctoral fellowships. The Discovery Grant fund has been preserved, although after inflation adjustments the average DG award has fallen by around 10% since 2007. This is particularly acute in terms of graduate student support as fees are rising, in turn driving up the required support from NSERC funds. Success rates have also fallen somewhat: following the change to the conference-based model, the total number of grants awarded has remained approximately constant despite the number of faculty growing by 17 positions. Despite concerns about their applicability to astronomy, the new innovation funding streams, such as Engage and CRDG programs, have been utilized by the field, with the first three years of funding bringing in close to \$0.25M of grants. However, the CREATE program appears to have been largely inaccessible to astronomy, with a single grant awarded in 2008 for the related field of astrobiology.

The overall organization of Canadian astronomy remains much as reported in 2010. The majority (80%) of researchers are university-based while the largest fraction of direct monetary support (approximately three times the NSERC funding) is channelled through the NRC. This highlights the importance of strong links between the university community and the NRC. In the era of TMT, where exceptional funding levels naturally imply high levels of expectation, we anticipate the need for NRC-university cooperation to become even more significant. We discuss this point in more detail in Chapter 8 Governance, Funding and Budgets.

In general, these statistics paint the picture of a comparatively healthy community undergoing sustainable growth, which nonetheless has challenges in terms of overall funding levels, especially in relation to student support. Looking to an increasingly competitive future, it is expected that there will be growing pres-

sure on funding to help attract the best and brightest.

9.2 Career flow

These data have significant implications in terms of career prospects and are now being closely monitored in the national education and skills context. By considering a flow analysis of the five ACURA surveys,²² it is estimated that roughly 80% of PhD graduates are able to find a PDF position. However, flow in and out of the country is not accounted for directly in this modelling. Thus the actual percentage of PhD graduates that find PDF positions could be different from what is reflected here, possibly even higher if Canada is a net exporter post-PhD. It is quite common for graduates of PhDs in Canada go abroad for their first PDF position.

The step from PDF positions to faculty is much more difficult. A flow analysis suggests that only 19% of PDF positions transition to faculty. Again, while factors of flow in and out of the country could impact this percentage, it is in moderate agreement with estimates from the PhD destinations survey conducted for LRP2010.

In a broader context, these numbers are in close agreement with a Conference Board of Canada analysis²³ that 19% of PhD graduates, across all disciplines, are employed as university professors. The number increases to 39% if any form of employment within post-secondary education is considered. It is clearly important to recognize that four out of five PhD students will not find employment in the professoriate. Improved preparedness for alternative careers, such as the provision of more transferrable skills, is clearly in the best interests of graduate students. Balancing this against the needs of adequate subject area development needs to be handled carefully.

²² “The Evolution of Astronomy and Astrophysics Populations” ACURA publication, R. Racine, 2014.

²³ http://www.conferenceboard.ca/topics/education/commentaries/15-01-06/where_are_canada_s_phds_employed.aspx

9.3 Broader subject area comparisons

Previous demographic surveys have not put in context the overall size of the astronomy community relative to other disciplines, such as biology or chemistry. This exercise was undertaken in 2013 as part of an ACURA report to the NRC entitled “The Thirty Meter Telescope and Astronomy in Canada”. We borrow from data compiled in that report here. Precise statistics are difficult to derive due to completeness concerns, although CAUT summaries provide good estimates with the proviso that detailed subject area breakdowns stopped being provided in 2010.

In terms of student numbers, overall undergraduate student numbers are approximately in the ratio 1:9:19:98 for astronomy to physics, to chemistry and lastly to biology. Biology remains overwhelmingly popular as an undergraduate degree which is unsurprising given that it is perceived to be a feeder into numerous health-related graduate programs. Growth rates in biology and chemistry (6% and 8%, respectively) both outpaced astronomy and physics (2% and 3%, respectively). The growth of undergraduate research (9%) noted in the ACURA census in the 2000–10 decade should be considered in the context of these overall population growth numbers: it suggests that while overall undergraduate numbers increased modestly, undergraduate students became much keener to gain research experience.

At the graduate level the ratios of student numbers are much closer, namely, 1:6:8:12 highlighting that the undergraduate to graduate flow is quite different across the sciences. At the graduate level, physics is approximately half the size of biology, a significant contrast to the almost factor of ten ratio at the undergraduate level. The growth rates of the populations are also broadly similar with biology at 5%, chem-

istry 4% and physics 3%, although the number for physics should be treated with caution as there appears to be a change in CAUT reporting for physics in 2004. The 4% growth rate for graduate astronomy reported by ACURA also matches these numbers closely. Overall, the growth of astronomy is healthy, and is not an outlier in the national science context.

9.4 Participation of women and minorities in astronomy

Using the departments included in the ACURA survey, a follow-up web-survey conducted by the MTRP suggests that the overall participation of women at the faculty level in Canadian astronomy is just under 18% (note not all websites give clear information on academic rank). CAUT data for astronomy from 2013, has a slightly lower value of 16% but is likely less complete. Within specific ranks, the CAUT percentages are: assistant professors 30%, associate professors 14%, and full professors 6%. This compares to 32%, 25%, and 15% for all of the sciences and technology areas grouped together. Even before consideration of the true value of the overall average, clearly women are under-represented within astronomy relative to the sciences at large. Moreover, the numbers for astronomy are comparatively unchanged compared to an independent survey commissioned by the CASCA Board in 2005,²⁴ which gave 31%, 18% and 4% respectively (no CAUT or ACURA data are available for this epoch). It is disturbing that there has been such little change in the overall percentage of associate professors given that the assistant to associate transition is frequently the most rapid career step, although a complete 2015 survey is clearly needed.

At the graduate student level, female enrolment in CASCA represents 46% of the

membership although this is not a complete census. The most recent CAUT data available is 2010, where it is reported 41% of MSc students in astronomy are female, while 33% of PhD students are. Based upon the LRP2010 PhD survey, and independent studies previously mentioned, there is evidence that fractional female participation is rising in astronomy, but only slowly and the leaky-pipeline effect appears to be operating. It is also worth emphasizing that studies have shown, most notably the Yates Committee on Gender Equity at McMaster University, that there are systemic inequalities for female faculty, including pay, even when adjusted for seniority and tenure.

Addressing these inequities is a challenge that all must accept. Notably the Australian decadal plan has made a recommendation that its institutions adopt positive hiring processes with a view to making the overall participation rate 33% by 2025. While positive hiring processes are important, it is worth recalling that the NSERC University Faculty Awards (UFA) program, which cost around \$2M per year over 10 years, was eventually put on hold since it could not address the place where inequity appears most impactful within the academe, namely the transition out of assistant professorships to senior ranks (occasionally referred to as a glass-ceiling issue). However, the UFA and earlier Women's Faculty Awards (WFA) programs have had a significant impact on female representation in Canadian astronomy: approximately 40% of female astronomy faculty have received funding from them.

There are alternative possibilities. Other than fellowships, awards for individuals undergoing career interruptions could be considered, as can changing assessment of productivity based upon the opportunity of an individual to contribute. One particularly innovative way of promoting an appreciation of the issues is to provide

24 <http://www.aas.org/cswa/status/2007/JUNE2007/WomenInCanadianAstronomy.html>

awards to institutions that take steps to advance the careers of women and minorities in astronomy, and the Pleiades Awards in Australia are a proven example.

Unfortunately, we are not aware of any statistics available on the representation of minorities in Canadian astronomy. This is a very significant issue that needs to be addressed, and a survey appears to be the only path forward.

Recommendation: *CASCA's newly formed Diversity and Inclusivity committee should restart CASCA's equity survey process, extending it to capture data on minority participation. From the data derived, policy recommendations should be formulated that either the LRPIC or LRP2020 can directly build upon.*

The recent reports of systemic violations of institutional sexual harassment policies by individuals at some US universities, has shocked the global astronomical community. The MTRP joins the CASCA Board of Directors in strongly condemning the actions of these individuals: such behaviour has no place in our professional academic and working environment. The MTRP fully endorses CASCA's ethics statement, and the implementation of a code of conduct at its annual meetings.

10 Discussion and summary comments

10.1 Project phasing of the TMT and SKA

As for LRP2010, the top-ranked projects in ground-based astronomy for the MTR are the TMT and SKA. However, there has been a significant shift in the schedules of both projects since 2010. In 2010 the most ambitious construction timelines for TMT envisaged the telescope constructed by 2016; at the time of writing the earliest construction can begin on Maunakea is fall 2016, and it could be later. Best estimates for the completion time for TMT are now 2024. For the SKA construction of Phase 1 has shifted from 2016–19 to 2018–23 with early science anticipated by 2020.

Nonetheless, the question must be asked: Can two world observatory projects be managed simultaneously by the Canadian astronomy community? In short, these two projects can be straightforwardly handled together. Firstly, while many astronomers work across multiple wavelengths, in practice the primary expertise of most university researchers is distinct to a given wavelength. Thus while there is no strict delineation between the optical astronomy and radio astronomy communities, there are sufficient numbers of researchers with primary interests in optical or radio astronomy for the projects to be more than adequately supported. Secondly, within the NRC the optical and radio astronomy programs are distinct from one another, meaning that resources will not be drawn from one at the expense of the other, again allowing both projects to move forward together.

10.2 The need for involvement in a dark energy mission

While some progress has been made since 2010 on involvement in one of the possible missions, the MTRP wishes to express significant concerns about the uncertainty faced in this area and the potential damage that could result by Canadian astronomy being “shut out” of these survey missions. The WFIRST mission, offering three distinct instrumentation capabilities and synergies with JWST, remains a highly interesting prospect to the Canadian community, yet great uncertainty surrounds what scientific involvement can be expected for Canadian researchers. The involvement of a small number of Canadians on science teams would clearly not be an appropriate return for an investment of several tens of millions of dollars, and the MTRP strongly suggests that researchers be involved in discussions with the US mission leaders on this front. At the same time, the Canadian-led CASTOR mission, which admittedly is in a different mission class, but nonetheless offers unique and synergistic capabilities, including science cases not available to either WFIRST or Euclid, has not been given sufficient support to advance to the point where it can be discussed within the international community.

It is worth emphasizing that dark energy missions are survey missions, something in which the Canadian astronomy community has considerable expertise by virtue of the success of MegaCam on the CFHT. Aside from producing data that addresses the dark energy question, the imaging produced in these surveys can address many other science questions of interest to the Canadian community. There are also numerous other synergies with upcoming or proposed Canadian

facilities such as JWST, TMT and MSE. The MTRP therefore strongly reaffirms the value of this science area.

10.3 Mid-scale facilities/projects

World observatories have capabilities that are unique and by definition are not (significantly) bettered elsewhere. The landscape is different for mid-scale facilities where competition in the landscape can evolve more quickly. Indeed it is possible that innovation in mid-scale level facilities can address small parts of larger-scale facility science cases, which is one of the reasons why the US decadal plan emphasized the value of mid-scale innovation. This report takes the philosophical position that recommendations by the MTRP at this level serve as a generic assessment of capability, and that a true assessment of mid-scale facilities for ground-based astronomy must be considered in peer reviewed competitions. The 2016–20 budget item “Midscale innovation” reflects this philosophy in terms of supporting CCAT, and contributions to the design and development of MSE and second generation instrumentation for TMT.

For space-based facilities the situation is more complex. Other than JWST, which the whole community remains extremely excited by, Canada’s contributions to space astronomy missions are generally small, at least when measured by international standards. Thus while recommending contributions to a CMB polarization mission, Athena and SPICA, only the CMB polarization mission is anticipated to need significant funding within the 2010–20 decade. However, both Athena and SPICA, at the time of writing, are unique capabilities. Indeed, unless the next US decadal plan supports a massive US mission in X-ray astronomy, the Athena mis-

sion can be viewed as the de facto “world observatory” for X-ray astronomy. The MTRP thus strongly endorses involvement in both Athena and SPICA, despite flying more than a decade out, and emphasizes the importance of determining what contributions can be made.

10.4 Budget justification and projections 2020–25

Although discussed in detail within the text, we here summarize the reasoning behind funding values given for each line item. The focus of this accounting is on equipment contributions and does not include, for example, CSA administration costs, or NRC Herzberg salaries. It is important to again emphasize that in almost all cases the numbers quoted must be expected to have some variance, and that the LRPIC and LRP2020 will be able to produce more accurate estimates as projects evolve.

The projections provided for 2020–25 are essentially approximate roadmaps, and in many cases participation or contribution levels are highly uncertain, this is particularly notable for second phase of the SKA which this report has not considered due to the immediacy of the first phase. One key exception is MSE, for which the overall costing is comparatively well understood although exact participation levels will be subject to negotiation between countries.

TMT

The April 6, 2015 announcement by the Government of Canada set the construction contribution at \$243.5M, as compared to the original LRP2010 request of \$305M. The additional \$20M budget listed for the 2016–25 period (\$5M from midscale innovation plus the \$15M noted in 2020–25) represents a contribution to second-generation instrumentation

projects that will be necessary to preserve facility share. This represents a nominal increase of \$5M in the 2010–20 decade, with the bulk of the funds being spent in 2020–30.

SKA

The \$60M figure quoted is likely towards the upper limit on the expected SKA1 contribution for Canada, and will ultimately be determined by an international agreement. A number of opportunities for contributions exist, although the selected technologies will be determined by SKA committee processes. The budget reaffirms that of LRP2010.

CCAT

The consortium of Canadian universities contributing to CCAT proposed a \$28M contribution to the project in 2014 via a CFI grant. Although overall costs remain uncertain at this point, this represents slightly under a one-quarter share of the final facility, approximately the same as the former share of the JCMT. This would give Canadian interests a strong voice in the operation of CCAT. A contribution of \$30M is thus included in the midscale innovation budget for 2016–20. This is an increase of \$15M over LRP2010 estimates.

MSE

Envisioned as a highly international project, the budget quoted for MSE is comparatively uncertain at this time, but based upon a \$250M total cost, \$40M (\$5M from midscale innovation 2016–20 and \$35M for 2020–25) represents a 16% share, consistent with involvement in both Gemini and TMT. Precise time requirements for these funds will become clear as the project progresses, although the bulk construction costs will likely be predominantly in the 2020+ era. The \$5M budget for 2016–20 represents a new request over LRP2010 (which did not budget for MSE construction) while the

majority of the construction costs are anticipated to occur in the 2020–30 decade.

WFIRST/CASTOR

The 5% share for Canadian participation in JWST, combined with a \$2B estimate for the WFIRST mission, places a similar Canadian contribution to WFIRST at \$100M (ignoring the notable variances in current exchange rates), which remains as proposed in LRP2010. However, it should be noted that the overall contribution value will be strongly constrained by the contributions that NASA desires and could be lower than this figure.

Costs for CASTOR remain uncertain and this report has recommended continuing work and a Phase 0 study be conducted to assess them in detail. A significant partnership for CASTOR will be an essential part of the costing.

CMB Polarization missions

Both the LiteBIRD and PIXIE missions have spacecraft and instrument costs in the \$200M range. The Canadian contribution is thus assessed at the 10% level, but will ultimately be determined by an international agreement on the equipment contribution. The MTRP emphasizes that these missions are targeted for launches in the early 2020s and will likely need funds on a comparatively short time scale. Thus the selected mission will be the only medium-scale space mission requiring funding in the entire 2010–20 decade. The \$20M budget represents a reduction of \$5M over the LRP2010 budget for SPICA and Athena (which are now both late 2020s missions).

Athena

Contributions to Athena, scheduled to launch in 2028, are the most uncertain of all missions and facilities highlighted in this report. The MTRP is therefore unable to place even an estimate against

this mission at the current time. However, emphasizing discussions elsewhere in this document, Athena remains the single most exciting X-ray astronomy facility that is currently moving ahead. Failing to secure participation in Athena will have a significant impact on the high-energy astrophysics community in Canada. This position matches LRP2010, in that a specific technology contribution to IXO could not be costed, and the budget of \$10M against IXO was specified for technology research and development only.

SPICA

Although this mission has evolved significantly since 2010, it continues to offer an unmatched spectroscopic capability. The \$10M budget for 2020–25 reaffirms the contribution suggested in LRP2010.

Small Payloads

This category merges recommendations given in LRP2010 for both balloon missions and microsatellites, and maintains the same funding level.

Post-doctoral fellow support

The cancellation of NSERC's Special Research Opportunity program had a strongly negative impact on the funding of PDFs. As in LRP2010, we recommend that this funding be reinstated at the level of \$700K per year, commensurate with the value of the SRO program to astronomy before its cancellation. An additional \$1M per year is recommended from the CSA in support of mission targeted PDFs, especially in relation to JWST. Aside from greatly improving the science return on investment and spurring more rapid advances, this funding increase would also help prevent Canadian researchers from being usurped from leadership positions in international collaborations due to a lack of resources. We emphasize that even these combined values should be considered absolute lower values for support.

Scaling shares of the JWST mission alone, either by observing time or population suggests that over \$2M per year should be provided for postdoctoral funding in Canada to match the equivalent US investment. In support of theoretical research, we reaffirm the suggestion to augment the CITA National Fellows grant, at \$200K per year. This will add four additional National Fellow positions and adjust for the fact there have been no inflationary increases in the grant since 2010. Post 2020, we have added an increase to account for inflation and allow for a full five year period. On a year-to-year comparison the requested funding level is \$0.77M higher than LRP2010.

Laboratory infrastructure investments

LRP2010 laid out detailed arguments for supporting a network of three major centres across the country, with funding levels for each centre priced at \$750K per year, plus an additional \$1M per year in instrument testbed support from CFI. Expenditures for the centres were envisaged as being spread 2/3 to NSERC and 1/3 to the CSA, reflecting the relative distributions of the development of ground-based versus space-based instrumentation. This funding has not been approved, and the situation has worsened with the suspension of the MRS program. While the loss of the MRS program impacted astronomy at the level of \$200K per year, the MTRP viewpoint is that merely replacing this funding is insufficient to generate innovative new techniques and technologies that are necessary to fully exploit the opportunities in second generation instrumentation for TMT, for example. We recommend funding at the level 1/3 that of LRP2010, namely \$1M per year, but believe this to be a justified number that replaces funding lost due to program suspensions, whilst enabling a funding stream that ensures continuity of personnel. We also note this number is the same as that quoted in the previous MTR. Post

2020 we have added a 40% increase on a year-to-year basis to reflect an expected, and necessary, build-up of expertise in support of major instrumentation innovation (TMT being a key motivation), and adjusted for a full five year period.

Outreach

While NSERC has not been able to fund outreach at the 1.5% level recommended in both previous LRPs, it should be noted that the NRC has acted on previous recommendations to use monetary funds in support of outreach. Unfortunately, recent cutbacks have curtailed this effort, particularly with the enforced closure of the Centre of the Universe. Given recent statements by the current President of NSERC that the PromoScience program will be strongly supported, we recommend support at the level of \$300K per year to be set aside for outreach purposes: \$100K per year going toward augmentation of NSERC PromoScience projects within astronomy (which would need to be competed, and thus the \$100K can be viewed as a fractional part of a much larger increase of the overall PromoScience budget), while a \$200K per year contribution from the NRC is broadly similar to prior commitments. The budget for 2020–25 is adjusted for the full five year period and adds an inflationary increase.

Funding for New Astronomy Facilities/Missions/personnel 2016–25

The 2016–20 budget is an update of LRP2010 for the remaining four years of the 2010–20 decade. The 2020–25 suggestions go beyond the LRP2010 framework and thus include new funding, although both Athena and SPICA have suffered delays moving them into the 2020 decade.

- 1) Midscale innovation includes CCAT, costs for developing facilities/instruments that will have primary construction in the 2020–25 decade, including MSE and second-generation instrumentation for the TMT, and new projects that may appear. It is anticipated that these funds will come largely from existing competitive programs.
- 2) At present, the costs and schedules of these projects are uncertain. However, they both fall into the “large” investment category with individual project costs (for Canadian contributions) in excess of \$100M.

	Project/Theme	2016–20 Amount
Ground	SKA Phase 1	\$60M
	Midscale innovation*	\$40M
	Sub total	\$100M
Space	Dark energy and surveys	\$100M
	CMB Polarization	\$20M
	Small payloads	\$5M
	Sub total	\$125M
People/Infrastructure	Postdoctoral funding	\$7.6M
	Laboratories	\$4M
Total		\$236.6M
Outreach	PromoScience and NRC	\$1.2M

10.5 List of MTR2015 Recommendations

Below is a complete summary of the recommendations developed by the MTR process. The ordering reflects appearance in the document and is not reflective of importance.

1. (page 20)	The MTRP strongly reaffirms the need for stable funding of university-based astrophysics laboratories, both as a generator of new instrumentation ideas as well as an important complement to the larger laboratory infrastructure present at NRC Herzberg.
2. (page 20)	The MTRP re-iterates the need for continued funding of productive Canadian small telescopes.
3. (page 21)	The MTRP reaffirms the value of increasing NSERC's support to CITA to augment the National Fellows program, which has proven exceptionally successful in attracting talented post-doctoral researchers to Canada, with four additional positions.
4. (page 22)	CASCA draft a mission statement on its EPO activities and goals.
5. (page 23)	Social media should be considered a key component of organizational outreach strategies. Appropriate resources, specifically funds, talent, energy, and time, should be allocated.
6. (page 23)	NSERC commit to expanding the PromoScience program budget, while NRC return to funding astronomy-related outreach at levels similar to the 2000–10 decade.
7. (page 27)	With access to a VLOT being the number one priority for ground-based optical-infrared astronomy, the MTRP reaffirms the importance of maintaining a “second-to-none” share in TMT. Since partner shares will also factor in future contributions to the observatory, the MTRP therefore strongly endorses ongoing development of second-generation instrument concepts and encourages the various teams to pursue funding.
8. (page 29)	The MTRP re-iterates the very high importance of Canada's technological and scientific participation in the next generation of radio telescope facilities. With TMT construction funds committed, access to the capabilities provided by SKA1 in the next decade is the top priority for new funds for ground-based astronomy. The MTRP re-iterates the high priority of mid and low-frequency radio R&D, and in particular the development of key technologies for SKA1 tender and procurement.
9. (page 31)	The MTRP strongly recommends that Canada enter into negotiations to join the intergovernmental organization that will oversee SKA1 construction and operations starting in 2017. An alternative to a treaty may be needed for Canada to join SKA1; this alternative must not significantly compromise Canada's role in SKA1 governance, access, or construction tender and procurement.
10. (page 32)	Canada should participate in a bid for ALMA development funding to build the ALMA Band 1 receivers, which would take advantage of Canadian skills and experience developed during the design and building of the Band 3 receivers. In addition, Canada should proceed quickly to identify other short-term and longer-term priorities for ALMA development work.
11. (page 33)	Canada should continue to be a major partner in CFHT, supporting its facility instrumentation project, SPIRou, and completion of the planned large surveys, as a 3.6 m telescope. Slippage in these projects should not delay redevelopment opportunities and priorities.
12. (page 35)	The MTRP strongly recommends that Canada develop the MSE project, and supports the efforts of the project office to seek financial commitments from Canadian and partner institute sources.
13. (page 35)	The MTRP recommends that Canada's participation in Gemini continue to be supported beyond the end of the 2016–21 International Agreement. The nature and level of that participation must be considered within the context of a coordinated plan for funding the operation of our ground-based facilities, together with any opportunities for broader access to the landscape of 8–10 m optical/IR telescopes.
14. (page 41)	The MTRP reaffirms the importance of next generation single-dish sub-mm facilities, and recommends that Canadian astronomers continue to pursue participation in CCAT, subject to the project meeting its original science goals. Construction contributions that keep key scientific, technical, and/or engineering work in Canadian companies and universities will provide the most return on investment.

15. (page 43)	The JCSA should work with CASCA and the CSA, to determine a precise input process for mission selection in space astronomy that is both transparent and equitable.
16. (page 45)	The MTRP reaffirms the exciting opportunity presented by WFIRST and its broad appeal to the Canadian community. In order to fulfil the LRPP recommendation we recommend that Canada begin negotiations to secure a significant (~5%) level of participation, at the earliest opportunity, so as to match NASA's accelerated schedule. This should include contributions to critical instrumentation that, preferentially, is synergistic with Canadian science interests, and funded participation on Science Investigation Teams for a representative number of Canadian scientists.
17. (page 46)	The MTRP strongly recommends that the CSA launch a Phase 0 study for CASTOR, with study results required within 12 months, so that this compelling project can be developed, presented, and competed in the international community. The LRPIC and JCSA should review the outcome of that study and make further recommendations as appropriate, well in advance of LRP2020.
18. (page 47)	The MTRP recognizes the unique role that Canada could play in an international CMB polarization satellite mission. The MTRP strongly recommends that the CSA engage in discussions with its sister agencies for a hardware and science role in a new mission such as LiteBIRD or other mission opportunity such as PIXIE that may arise in the immediate future.
19. (page 49)	The MTRP recommends that Canada continue to explore the possibility of contributing to the science instrumentation on Athena, as well as the cost and the access to the mission that would be gained from such a contribution.
20. (page 50)	The MTRP recommends that Canada explore the possibility of contributing elements of the Fabry-Perot instrument to SPICA, as well as the cost and the access to the mission that would be gained from such a contribution.
21. (page 51)	The MTRP recommends that Canada continue to support small-scale exploratory satellite projects and balloon-borne missions through regular calls for proposals, and that the CSA introduce regular calls for proposals for nano- and microsatellite opportunities and contributions to instrumentation on larger missions, so that these types of projects can also proceed through a competitive funding process.
22. (page 52)	The MTRP reaffirms the essential importance of continuing science support to exploit our investment in JWST as well as other CSA-supported missions. This should include funding workshops and help centres to enable the community to ramp up expertise prior to launch, as well as a mechanism for funding postdoctoral fellows to work on and with JWST data.
23. (page 57)	CC provide services such as authentication/authorization, and efficient distributed storage platforms that encompass both archiving and user spaces in a scalable way. Services like this will enable the development of increasingly sophisticated analysis platforms.
24. (page 58)	Given the increasingly blurred relationship between data and analysis products, the MTRP recommends that the Agency Committee for Canadian Astronomy (ACCA) meet to discuss possible strategies to avoid policy traps that preclude the funding of the development of critical and innovative software infrastructure for CAN-FAR.
25. (page 60)	An NRC Herzberg Advisory Board, constituted of senior representatives of academia, including both administrators and scientists, as well as industrial representatives, should be established to advise on the portfolio and programs of NRC Herzberg.
26. (page 62)	The MTRP reiterates the importance and value of the CIFAR Cosmology and Gravity program, which has been of exceptional benefit to Canadian astrophysics. The community is strongly encouraged to seek a further renewal of the program.
27. (page 64)	The MTRP reiterates the key role that PDFs play in research capability and facility commissioning, and hence reaffirms the high importance of NSERC funding a postdoctoral program in support of Canada's access to major facilities.
28. (page 66)	CASCA's newly formed Diversity and Inclusivity committee should restart CASCA's equity survey process, extending it to capture data on minority participation. From the data derived, policy recommendations should be formulated that either the LRPIC or LRP2020 can directly build upon.

10.6 Concluding remarks

Canadian astronomy is in many ways in a better situation than it was in 2010. The commitment to the TMT cannot be understated in terms of importance not only to current researchers, but also to attracting a new generation of researchers who will ultimately be the individuals that benefit the most from this facility. Yet, as has been outlined in this report, a properly functioning and diverse research ecosystem requires access to a range of wavelengths, and facilities at a range of investment levels. LRP2010, and this MTR, present a coherent and carefully detailed plan to build this absolutely necessary capability for Canada.

Like almost all spheres of life, the astronomy research landscape is more complex than it has ever been. Phasing of projects is a challenge, as are managing the exacting international partnerships that are necessary in funding these new facilities. Yet, at the same time, these partnerships

bring with them tremendous possibilities for collaboration and learning, both scientific and cultural, as well as new, and in many cases unforeseen, economic opportunities. The most heavily cited Canadian astronomy facility, the CFHT, was a success thanks to a successful and strong international partnership. And as the world changes, so do our international partners. Canadian astronomy is front and centre in forging new collaborative links with both China and India, whilst maintaining our close link with our US neighbours.

The history of Canadian astronomy is rich with accomplishment. The MTRP salutes a community that can rightfully stand up and be proud of its achievements, and thanks all the supporters of Canadian astronomy that have helped make this possible. We look forward to seeing a continued and strong partnership of researchers and students with industry, government and, most importantly, the Canadian public.

The history of astronomy, and science generally, tells us that the most startling discoveries are unanticipated. Unveiling the cosmos will reveal wonders we have yet to imagine.

11 Appendices

11.1 Appendix A: Acronyms, Abbreviations and Context

ACCA	Agency Committee on Canadian Astronomy
ACEnet	Atlantic Computational Excellence Network
ACURA	Association of Canadian Universities for Research in Astronomy
AGN	Active Galactic Nucleus
ALMA	Atacama Large Millimeter Array
ALTAIR	ALTitude conjugate Adaptive optics for the InfraRed (Gemini)
AO	Adaptive Optics; also Announcement of Opportunity
arcsec	Arcsecond, angular measure, 1/3,600 of a degree
ASKAP	Australian Square Kilometre Array Pathfinder
ASTRONET	European Astronomy Strategic Plan 2010–2030
Astro2010	New Worlds, New Horizons (US Decadal Survey)
AU	Astronomical Unit, the Earth-Sun distance
BLAST	Balloon-borne Large-Aperture Sub-millimeter Telescope
CADC	Canadian Astronomy Data Centre (HIA)
CANARIE	Canada's Advanced Research and Innovation Network
CANFAR	Canadian Advanced Network for Astronomical Research
CASCA	Canadian Astronomical Society
CASTOR	Cosmological Advanced Survey Telescope
CAUT	Canadian Association of University Teachers
CC	Compute Canada
CCA	Council of Canadian Academies
CCAT	Cerro Chajnantor Atacama Telescope
CCD	Charge Coupled Device
CFHT	Canada-France-Hawaii Telescope
CFI	Canadian Foundation for Innovation
CHIME	Canadian Hydrogen Intensity Mapping Experiment
CIFAR	Canadian Institute for Advanced Research
CITA	Canadian Institute for Theoretical Astrophysics
CMB	Cosmic microwave background
CRC	Canada Research Chair
CSA	Canadian Space Agency
CST	Canadian Space Telescope, now CASTOR
CU	Centre of the Universe (outreach facility at HIA, Victoria)
CTIO	Cerro Tololo InterAmerican Observatory

DAO	Dominion Astrophysical Observatory
DRAO	Dominion Radio Astrophysical Observatory
DSL	Dynamic Structures Limited
E-ELT	European Extremely Large Telescope
EBEX	E and B balloon experiment
ELT	Extremely Large Telescope
ESA	European Space Agency
ESO	European Southern Observatory
EVLA	Expanded Very Large Array
FAST	Flight for Advancement of Science and Technology
FGS	Fine Guidance Sensor
FTS	Fourier Transform Spectrometer
FUSE	Far Ultraviolet Spectroscopic Explorer
GPI	Gemini Planet Imager
GPU	Graphics Processing Unit
HIA	Herzberg Institute of Astrophysics, now NRC Herzberg
HPC	High Performance Computing
HQP	Highly qualified personnel
HST	Hubble Space Telescope
ICT	Information and Communication Technologies
IFU	Integral Field Unit
IR	infrared
ISM	Interstellar medium
IXO	International X-ray Observatory
JAXA	Japanese Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope
JWST	James Webb Space Telescope
LAE	Laboratoire d'Astrophysique Experimentale
LIGO	Laser Interferometer Gravitational Wave Observatory
LiteBIRD	"Light" satellite for B-mode polarization and Inflation from cosmic microwave Radiation Detection
LNA	Low noise amplifier
LRP	Long Range Plan
LRPIC	Long Range Plan Implementation Committee
LRPP	Long Range Plan Panel
LSST	Large Synoptic Survey Telescope
ly	Light year
MeerKAT	"More of the" Karo Array Telescope
MIRES	Mid-infrared Echelle Spectrometer (TMT)

MIRI	Mid-infrared Instrument (JWST)
MOST	Microvariability and Oscillation of Stars satellite
MRS	Major Resources Support program (NSERC)
MSE	Maunakea Spectroscopic Explorer
MTRP	Mid-Term Review Panel
NAPRA	North American Program in Radio Astronomy
NFIRAOS	Narrow Field Infrared Adaptive Optics System (TMT)
ngCFHT	Next generation CFHT, now the Maunakea Spectroscopic Explorer
NIR	Near infrared
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council of Canada
NSERC	Natural Sciences and Engineering Research Council of Canada
NSF	National Science Foundation
ODIN	Swedish-Canadian sub-mm satellite
OMM	Observatoire de Mont Mégantic
ORAN	Optical Regional Advanced Network
PDF	Post-doctoral fellow
PEARL	Polar Environment Atmospheric Research Laboratory
PI	Principal Investigator
PIXIE	Primordial Inflation Explorer
PSE	Post-Secondary Education
SCUBA	Submillimetre Common User Bolometer Array
SDSS	Sloan Digital Sky Survey
SETI	Search for Extraterrestrial Intelligence
SITELLE	Imaging Fourier Transform spectrometer (CFHT)
SKA	Square Kilometre Array
SNOLab	Sudbury Neutrino Observatory Lab
SPICA	Space Infra-Red Telescope for Cosmology and Astrophysics
SPIDER	Balloon-borne polarimeter for studying the CMB
SPIRou	Spectro-Polarimètre Infra-Rouge
SRO	Strategic Research Opportunity
SSEP	Space Sciences Exploration Program
STIC	Science, Technology and Innovation Council
TFI	Tunable Filter Imager (JWST)
TMT	Thirty Meter Telescope
UTIAS	University of Toronto Institute for Aerospace Studies
UVIT	Ultraviolet Imaging Telescope on the Astrosat satellite

VLA	Very Large Array
VLBI	Very Long Baseline Interferometry
VLOT	Very Large Optical Telescope
VLT	Very Large Telescope (ESO)
WFIRST	Wide Field Infrared Survey Telescope
WIDAR	Wideband Interferometric Digital Architecture
WMAP	Wilkinson Microwave Anisotropy Probe
z	Redshift (a measure of distance in the Universe)

Angular scales

This report frequently refers to the angular size of objects on the sky. For reference, the full moon is approximately 0.5 degrees in diameter, which is equivalent to 30 arcminutes (60 arcminutes constituting one degree). The human eye has a resolving power of approximately one arcminute. The limit of resolution due to distortion in the atmosphere is approximately one arcsecond, with 60 arcseconds constituting an arcminute. Resolutions significantly higher than this in optical wavelengths from the ground require adaptive optics techniques to correct for atmospheric distortions.

11.2 Appendix B: Table of LRP2010 recommendations

For reference, a summary of recommendations from LRP2010 is given below. These recommendations are numbered according to the ordering of material in the text, and *not* according to priority or ranking.

1	Canada should continue to be a major partner in CFHT, and should support and participate in new instrumentation projects (specifically 'Imaka, SPIROU, and GYES). These instruments should have a five year operations window prior to any anticipated redevelopment of the CFHT site.
2	The LRPP recommends that Canada's participation in Gemini be reconsidered as we reach the point that Canada's VLOT project requires operating funds.
3	Canada should participate in a bid on the provision of ALMA Band 1 receivers to take advantage of Canadian skills and experience developed during the design and building of the Band 3 receivers. In addition, Canada should proceed quickly to identify other short-term and longer-term priorities for ALMA development work.
4	The LRPP reaffirms its previous (MTRC) recommendation to phase out Canada's involvement with the JCMT as our various scientific and technical commitments are completed, and to transfer its operating support to ALMA. The LRP2010 also recommends that extending JCMT operation beyond March 31st 2012 should be considered only if this does not affect ALMA operations, and only after (i) a performance review of SCUBA-2, and (ii) an assessment of the scientific impact of the (descope) SCUBA-2 surveys.
5	The LRPP recommends that the Canadian SKA Board of Directors, and other principal players involved in the SKA, be proactive in encouraging use of the EVLA to build up an SKA user base in Canada.
6	Completing and launching JWST is the top priority for Canadian space astronomy. CSA should continue working diligently with its international partners (NASA, ESA) to bring this observatory into operation as soon as possible. More specifically, sufficient resources should be allocated to encompass the costs inherent in a launch delay of JWST, and to ensure the success of the science-critical made-in-Canada Tunable Filter Imager. Once completed, sufficient support must be provided to allow timely pre-flight calibration and in-flight operational support of this instrument, which is of special interest to the Canadian community.
7	The LRPP reiterates the need for the funding of university-based experimental astrophysics laboratories in Canada for both ground-based and space-based instrumentation and technology development, and recommends that renewable funding programs be available from NSERC and CSA to support these activities. The LRPP further encourages NRC to support Industrial Chairs at Canadian universities. Coordination between the funding agencies is a key to achieving these goals.
8	The LRPP recommends continuing funding from NRC and NSERC for the productive small telescopes discussed above, with an emphasis on increasing remote access/queue mode observing to serve the widest possible community.
9	The LRPP recommends that CITA's NSERC support be increased by 12%, so that, so that, in addition to continuing its existing programs that attract top researchers to Canada both in the short and long term, it can add four new PDFs to the CITA National Fellows Program.
10	Compute Canada funding should be doubled to bring us up to at least 2/3 of the G8 average HPC funding per GDP. At least 1/5 of this funding should go towards encouraging user innovation through research support, and to the provision of HPC consultants. Compute Canada should also budget funds to ensure a "Tier 1" facility is available to researchers.
11	The LRPP recommends that Compute Canada move to fully support users with cloud computing requirements.
12	The LRPP reiterates the need for a coherent Canadian Data Management Policy. As observatories become more dependent on data analysis, end-to-end management of data, including decommissioning archiving, needs to be a critical part of project development. A working group from the NRC (CADC) and CASCA should be formed to address this point, particularly focusing on the needs of the "world observatories".
13	Timely access to a VLOT remains Canada's number one priority for large projects in ground-based optical-infrared astronomy over the next decade. Canadian participation in a VLOT needs to be at a significant level, such that it will not be treated as a "lesser partner" in scientific, technical, and managerial decisions.

14	The LRPP recommends that Canada pursue a “second-to-none” share of TMT. This recommendation is contingent on a TMT construction start no later than 2014. Funding for Canada’s TMT participation should be provided at a level that ensures that a 2014 (or earlier) start is possible. The continued participation of HIA is essential to maintain Canadian presence in the TMT project.
15	If by early 2012 it appears that a 2014 construction start for TMT will not be feasible, then the LRPP recommends that we take steps to become a partner in the E-ELT project by joining ESO, and that we discontinue our partnership in TMT.
16	The LRPP reaffirms the importance and very high priority of Canada’s participation in the SKA, which it anticipates will become the top priority following VLOT. Canada should continue its current path in the engineering design and prototype development of SKA elements, leading to participation in the pre-construction design phase, and should continue to seek opportunities to build components where Canada has experience and an international reputation. SKA R&D is the highest priority medium-scale project over the next decade. The decision as to how and when Canada should enter the construction phase of SKA should await further reviews of SKA project development, a more accurate cost estimate, better understanding of international prospects, and a better knowledge of timing for funding a construction start.
17	The LRPP views CHIME as a key medium-scale experiment that could have high scientific yield at modest cost, and encourages the proposing team to vigorously pursue funding for this experiment. The LRPP endorses the project provided that a detailed study confirms its budget and the feasibility of its technical design and science goals.
18	The LRPP recommends that Canadian astronomers pursue participation in CCAT. More specifically, funds at the level \$0.9M should be devoted to R&D, and to conducting a thorough investigation of potential Canadian contributions (instrumentation and/or infrastructure).
19	Site testing at PEARL should be funded and continued until the image quality at the site can be fully characterized. This site testing requires continued support of the PEARL facility. In addition, testing should be extended to at least one additional, preferably higher altitude, site in the High Arctic. If the superlative image quality of Arctic sites is confirmed, then the LRPP recommends a design study and the development of a science case for a small (1–4 metre) telescope, and technical studies on telescope construction and operation in polar environments. This would be followed by telescope construction, if the design and implementation are determined to be cost effective.
20	The LRPP recommends that Canada develop the ngCFHT concept (science case, technical design, partnerships, timing).
21	The LRPP recommends that a cost exercise be started immediately by CSA and Canadian astronomers to (i) identify possible instrumentation contributions to space missions of interest, and (ii) estimate the costs to Canada of these missions.
22	The LRPP recommends that Canadian astronomers participate in a major wide-field Dark Energy satellite mission. Joining Euclid or WFIRST as a significant partner would fulfill this recommendation, provided that we can (i) negotiate a partnership in the leading mission, and (ii) identify a contribution to the satellite instrumentation. Alternatively, a Canadian Space Telescope (CST) could be developed as a component of a Dark Energy experiment.
23	The LRPP recommends ASTRO-H as its top priority small-scale space mission. The LRPP commends CSA for its rapid handling of this opportunity.
24	The LRPP strongly recommends Canadian R&D involvement in IXO as its number-one medium-scale space priority. This is because of its excellent foreseen scientific capabilities that will be a superb match for the expertise of the Canadian HEA community, but also with an eye toward capitalizing on technical expertise gained from fabrication, implementation and calibration of the ASTRO-H metrology system. Involvement with IXO is consistent with CSA’s mandate of growing experience and capability.
25	The LRPP recommends that the CSA and other funding agencies develop procedures that enable them to react quickly to international opportunities (like that offered by ASTRO-H), which often have timelines and scheduling that are beyond our control. Such involvement, once established, has the potential to pave the way toward future projects with even more Canadian involvement, and eventual Canadian leadership.
26	The LRPP gives Canadian participation in SPICA very high priority under medium-scale space projects.
27	Canada is a world leader in micro- and nano-satellite technology. The LRPP strongly supports this program as a cost-effective way of answering highly targeted science questions. The LRPP recommends that the CSA issue a call for proposals for micro- and nano-satellites so that new projects can proceed through a competitive funding process.

28	The LRPP notes the continued scientific importance of balloon-borne experiments, and strongly reinforces the need to continue these missions, both for their scientific potential, and also as a cost-effective means of accessing a near-space environment for technology development and demonstration.
29	The LRPP recommends that NRC and ACURA negotiate a cooperative agreement to manage HIA. This would preserve NRC's responsibility for operating and administering observatories established or managed by the Federal Government. The CSA should be involved as well in order to permit a review of options for its participation in this cooperative management. NSERC and CFI should be invited to play a less formal role as observers in any new governance structure since their participation would act to improve communication among the various agencies for the support of astronomy.
30	All of the relevant funding agencies in Canada should cooperate to recommend to the Federal Government a standing process for funding Big Science in Canada. The process should involve a panel of internationally recognized Canadian and non-Canadian scientists, and a rigorous and extensive peer review.
31	The LRPP recommends that the LRP Implementation Committee collect data following the next several NSERC DG competitions, in order to assess the impact of the new conference model evaluation scheme on astronomy. The results of this analysis should be communicated to NSERC and the astronomical community.
32	We recommend that the CSA move towards a system that enhances the role and involvement of science teams in instrument delivery.
33	The success of the CIFAR Cosmology and Gravity program has been of exceptional benefit to Canadian astrophysics. We strongly encourage the community to seek a further renewal of the program.
34	The LRPP recommends that CSA set aside funds in the SSEP program to provide support for four PDFs in support of JWST and other CSA supported missions. This investment will help ensure that the exceptional data expected from these missions will be utilized to their full extent.
35	The LRPP recommends that NSERC fund a postdoctoral fellowship program in support of Canada's access to major international facilities. The investment in this program should be proportional to the requisite hardware investment.
36	Graduate programs should strongly consider adding some element of outreach, either training or project requirements, to their programs.
37	The LRPP recommends that the "AstronomyCanada.ca" website be co-developed with a brand awareness campaign led by the professional community.
38	The LRPP reiterates the value of investing a 1.5% fraction of government funding of new large-scale projects into outreach.
39	It is important that Canadian funding agencies recognize the potential importance of astronomy projects of small to intermediate scale that develop on rapid time scales, and that are therefore not included in the LRP Report. Such projects may have a strong impact on science and in training of HQP for involvement in Very Large Facilities within the plan.
40	The LRPP recommends that a standing LRP Implementation Committee (LRPIC) be formed to handle "real-time" decisions that arise from the LRP2010 report concerning the future evolution of Canadian Astronomy.

11.3 Appendix C: CSA Budgets 2005–15

The MTRP expresses thanks to Dr. Denis Laurin for passing on these figures.

Mission	Launch	FY 05/06	FY 06/07	FY 07/08	FY 08/09	FY 09/10	FY 10/11	FY 11/12	FY 12/13	FY 13/14	FY 14/15	Total*
FUSE	1999	0.2	0.1									3.0
ODIN	2001	0.6	0.3	0.3	0.3	0.3						5.5
MOST	2003	1.0	1.0	0.8	1.0	0.7	0.7	0.9	0.8	0.6	0.5	19.1
BLAST	2005	0.2	0.3	0.3								1.8
Herschel	2009	4.4	1.4	0.8	0.9	0.9	1.0	1.0	0.8	0.7	0.7	19.3
Planck	2009	0.3	0.4	0.6	0.4	0.4	0.5	0.4	0.3	0.3	0.3	8.0
ASTROSAT	2015	1.6	1.5	1.0	1.2	1.3	0.2	0.3	0.2	0.5	0.4	8.9
EBEX	2009				0.2	0.5						0.7
NEOSSat	2013	0.3	0.3	2.3	1.1	2.4	1.0	1.4	3.1	2.2	2.1	16.3
JWST	2018	8.6	22.8	30.9	34.7	28.7	11.4	7.8	6.1	5.7	10.1	170.9
CADC		0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	3.8
BRITE	2012						0.7	2.4	0.4	0.1		3.6
ASTRO-H	2016						0.6	1.5	3.2	2.5	1.4	9.1
Total		17.7	28.5	37.1	40.2	35.5	16.2	15.8	15.1	12.7	15.7	270

a.) Total figures are summed over all mission years, including those going back to FY00/01. Numbers should be considered approximate.

b.) Concept studies and grants are not included, and FUSE and ODIN do not show full mission costs.

c.) MOST, ASTROSAT, Herschel, Planck, JWST, Astrosat, and ASTRO-H include scientific support.

d.) NEOSSat is jointly funded by DRDC and CSA (approximately 50/50). Figures above show only CSA funding and operations.

11.4 Appendix D: Table of Mid-term Review panellists

Member	Affiliation	Role
Dr. Michael Balogh	University of Waterloo	
Dr. David Crampton	National Research Council	Ex-officio
Dr. Matt Dobbs	McGill University	
Dr. Kristine Spekkens	Royal Military College of Canada	Vice-Chair
Dr. Michael Strauss	Princeton University	External Member
Dr. Robert Thacker	Saint Mary's University	Chair
Dr. Marten van Kerkwijk	University of Toronto	
Dr. Kim Venn	University of Victoria	
Dr. Christine Wilson	McMaster University	

