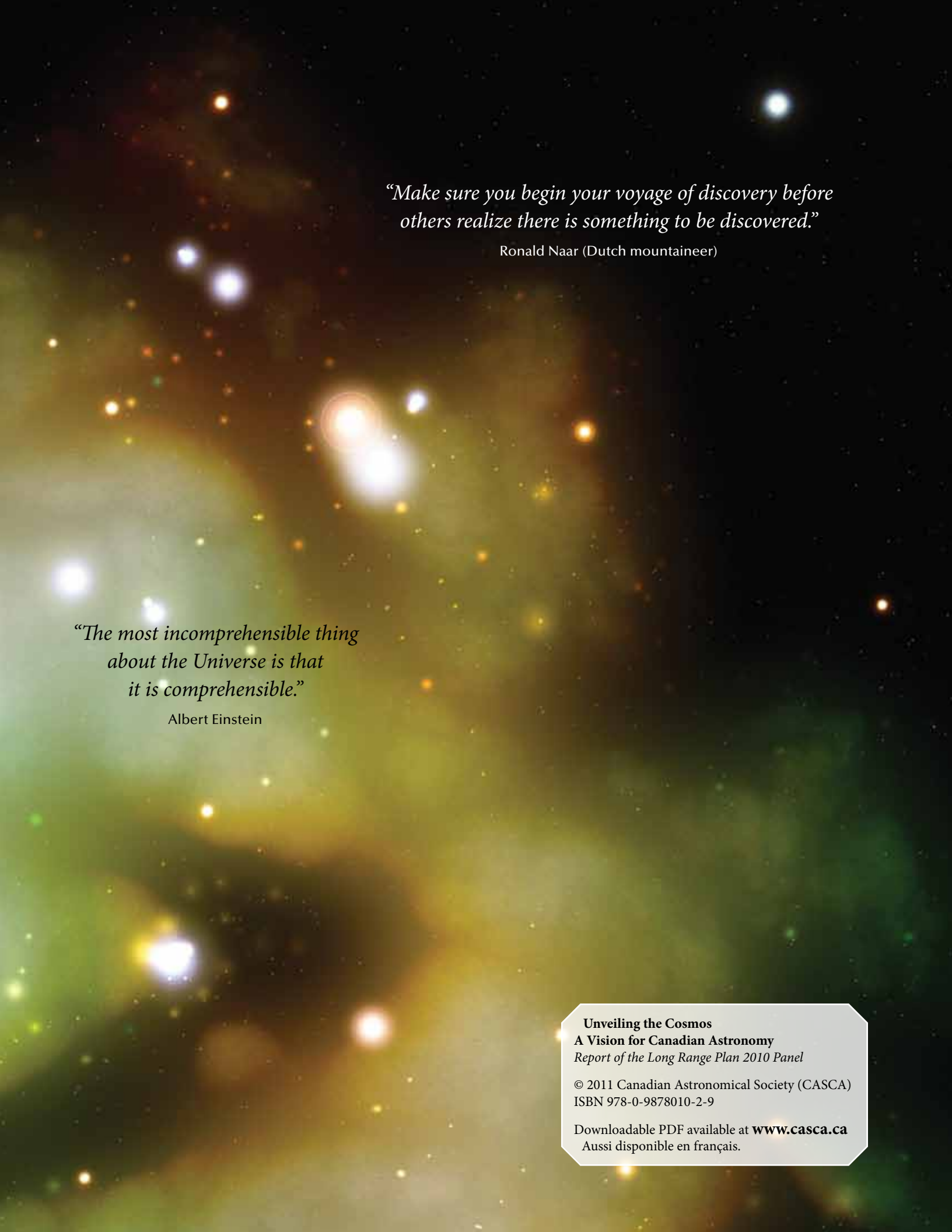


# Unveiling the Cosmos

*A Vision for Canadian Astronomy*

Report of the Long Range Plan 2010 Panel





*“Make sure you begin your voyage of discovery before  
others realize there is something to be discovered.”*

Ronald Naar (Dutch mountaineer)

*“The most incomprehensible thing  
about the Universe is that  
it is comprehensible.”*

Albert Einstein

**Unveiling the Cosmos**  
**A Vision for Canadian Astronomy**  
*Report of the Long Range Plan 2010 Panel*

© 2011 Canadian Astronomical Society (CASCA)  
ISBN 978-0-9878010-2-9

Downloadable PDF available at [www.casca.ca](http://www.casca.ca)  
Aussi disponible en français.

# Table of Contents

|  |    |   |    |
|--|----|---|----|
| <b>Acronyms and Abbreviations</b> .....  | iv | <b>4 New Ground-Based Facilities</b> .....                                    | 51 |
| <b>Introduction</b> .....  | 1  | 4.1 Very Large Facilities .....   | 51 |
| <b>Executive Summary</b> .....   | 5  | 4.1.1 Very Large Optical Telescopes .....                                     | 51 |
| <b>1 Overview of the LRP Process</b> .....   | 13 | 4.1.2 The Square Kilometre Array (SKA) .....                                  | 55 |
| 1.1 Overview of Canadian Astronomy .....   | 13 | 4.2 Medium- and Small-Scale Projects .....                                    | 58 |
| 1.2 LRP2000 and MTR2005 .....  | 13 | 4.2.1 CHIME .....   | 58 |
| 1.3 Changes in Landscape over the Past Decade .....                                  | 14 | 4.2.2 CCAT .....  | 59 |
| 1.4 LRP2010 .....  | 15 | 4.2.3 Astronomy in the High Arctic .....                                      | 60 |
| 1.5 Relationship with the US and European<br>Long-Term Plans for Astronomy .....     | 15 | 4.2.4 Next Generation CFHT .....  | 61 |
| <b>2 Science</b> .....   | 17 | <b>5 New Space Facilities</b> .....   | 65 |
| 2.1 An Overview of Astronomy<br>and Astrophysics in 2010 .....                       | 17 | 5.1 Dark Energy .....   | 65 |
| 2.2 Canadian Astronomy Highlights<br>of the Past Decade .....                        | 20 | 5.2 High Energy Astrophysics .....  | 67 |
| 2.3 Canadian Astronomical Research in<br>an International and National Context ..... | 22 | 5.3 Far IR .....  | 69 |
| 2.3.1 International Context .....  | 22 | 5.4 Micro- and Nano-satellites .....  | 69 |
| 2.3.2 National Context .....   | 24 | 5.5 Balloon Missions .....  | 71 |
| <b>3 Existing Facilities and Institutes</b> .....                                    | 27 | <b>6 Funding and Governance</b> .....   | 73 |
| 3.1 Ground-based Facilities .....  | 27 | 6.1 Funding of Canadian<br>Astronomy – Introduction .....                     | 73 |
| 3.1.1 CFHT .....   | 27 | 6.2 Canadian Astronomy Funding in<br>an International Context .....           | 74 |
| 3.1.2 Gemini .....   | 29 | 6.3 Governance of Canadian Astronomy .....                                    | 76 |
| 3.1.3 ALMA .....   | 30 | 6.4 Discussion of individual agencies .....                                   | 78 |
| 3.1.4 JCMT .....   | 32 | 6.4.1 NSERC .....   | 78 |
| 3.1.5 EVLA .....   | 33 | 6.4.2 CFI .....   | 80 |
| 3.2 Space Facilities .....   | 35 | 6.4.3 CSA .....   | 80 |
| 3.2.1 JWST .....   | 36 | 6.4.4 CIFAR .....   | 81 |
| 3.2.2 Herschel .....   | 37 | <b>7 Demographics</b> .....   | 83 |
| 3.3 Institutes and Laboratories .....  | 38 | 7.1 Introduction and Trends .....   | 83 |
| 3.3.1 HIA .....  | 38 | 7.2 Student Training .....  | 84 |
| 3.3.2 University-based Experimental<br>Astrophysics Laboratories .....               | 40 | 7.3 Postdoctoral Fellows .....  | 84 |
| 3.3.3 Small Telescopes in Canada .....   | 41 | <b>8 Astronomy and Society</b> .....  | 87 |
| 3.3.4 CITA .....   | 44 | 8.1 Astronomy and Canada's Strategic Plan<br>for Science and Technology ..... | 87 |
| 3.3.5 Perimeter Institute .....  | 44 | 8.2 Economic Benefits of Astronomy .....                                      | 89 |
| 3.4 Computational Resources,<br>CADIC and Networks .....                             | 45 | 8.3 Education and Public Outreach .....                                       | 91 |

|          |  |    |
|----------|--|----|
| <b>9</b> | <b>Summary of Priorities</b> .....                     | 95 |
| 9.1      | New Ground-Based Facilities.....                       | 95 |
| 9.2      | New Space-Based Facilities .....                       | 96 |
| 9.3      | Outreach, Infrastructure,<br>and Human Resources ..... | 97 |
| 9.4      | Concluding Remarks.....                                | 98 |
| 9.5      | Summary of Recommendations .....                       | 99 |

## Appendices

|  |     |
|--|-----|
| Appendix A – The Long Range Plan 2010.....                           | 105 |
| A.1 Terms of Reference .....   | 105 |
| A.2 LRP Panel Members.....   | 107 |
| A.3 LRP2010 Activities .....   | 107 |
| Appendix B – Funding Details.....                                    | 108 |
| Appendix C – Student Training .....                                  | 113 |
| Appendix D – Postdoctoral Fellows .....                              | 115 |
| Appendix E – International Funding .....                             | 116 |
| Appendix F – Examples of Industry-<br>Astronomy Success Stories..... | 117 |
| Appendix G – ESO Working Group Report.....                           | 120 |





# Acronyms and Abbreviations

|           |   |
|-----------|---|
| 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 Millimetre Array  |
| ALTAIR    | ALTitude conjugate Adaptive optics for the InfraRed (Gemini)                  |
| AO        | Adaptive Optics; also Announcement of Opportunity                             |
| arcsec    | Arcsecond, angular measure, 1/3600 of a degree                                |
| ASKAP     | Australian SKA Pathfinder   |
| ASTRONET  | European Astronomy Strategic Plan 2010-2030                                   |
| Astro2010 | New Worlds, New Horizons (US Decadal Survey)                                  |
| ATCA      | Australia Telescope Compact Array   |
| 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                           |
| CARMA     | Combined Array for Research in Millimetre-wave Astronomy                      |
| CASCA     | Canadian Astronomical Society   |
| 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  |
| CGPS      | Canadian Galactic Plane Survey  |
| CHIME     | Canadian Hydrogen Intensity Mapping Experiment                                |
| CIF       | Citation impact factor  |
| CIFAR     | Canadian Institute for Advanced Research                                      |
| CITA      | Canadian Institute for Theoretical Astrophysics                               |
| CLUMEQ    | Consortium Laval, Université du Québec, McGill and Eastern Quebec HPC Network |
| CMB       | Cosmic microwave background   |
| CO        | Carbon monoxide   |
| CRC       | Canada Research Chair   |
| CSA       | Canadian Space Agency   |
| CST       | Canadian Space Telescope  |
| CU        | Centre of the Universe (outreach facility at HIA, Victoria)                   |
| CTIO      | Cerro Tololo InterAmerican Observatory  |
| DAO       | Dominion Astrophysical Observatory  |

|       |   |
|-------|---|
| DI    | Dunlap Institute, U. Toronto                          |
| DRAO  | Dominion Radio Astrophysical Observatory              |
| DSL   | Dynamic Structures Limited                            |
| DSP   | Digital Signal Processor                              |
| DWG   | Discipline Working Group (CSA)                        |
| E-ELT | European Extremely Large Telescope                    |
| EBEX  | E and B balloon experiment                            |
| ELT   | Extremely Large Telescope                             |
| EMC   | Electromagnetic compatibility                         |
| 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                                  |
| FPGA  | Field Programmable Gate Array                         |
| FTS   | Fourier Transform Spectrometer                        |
| FUSE  | Far Ultraviolet Spectroscopic Explorer                |
| GAP   | Gemini Assessment Point review panel and report       |
| GPI   | Gemini Planet Imager                                  |
| GPU   | Graphics Processing Unit                              |
| GYES  | Proposed multi-fibre spectrograph for CFHT            |
| HIA   | Herzberg Institute of Astrophysics                    |
| HIFI  | Heterodyne Instrument for the Far Infrared (Herschel) |
| HII   | Ionized hydrogen                                      |
| HPC   | High Performance Computing                            |
| HPCVL | HPC Virtual Laboratory (eastern Ontario)              |
| HQP   | Highly qualified personnel                            |
| HST   | Hubble Space Telescope                                |
| ICT   | Information and Communication Technologies            |
| IFU   | Integral Field Unit                                   |
| IR    | infrared  |
| ISIS  | Institute for Space and Imaging Studies, Calgary      |
| 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 Expérimentale             |
| LIGO  | Laser Interferometer Gravitational Wave Observatory   |

## Acronyms and Abbreviations (continued)

|            |   |
|------------|---|
| LISA       | Laser Interferometer Space Antenna                          |
| LNA        | Low noise amplifier   |
| LRP        | Long Range Plan   |
| LRPIC      | Long Range Plan Implementation Committee                    |
| LRPP       | Long Range Plan Panel                                       |
| LSST       | Large Synoptic Survey Telescope                             |
| MeerKAT    | Karoo Array Telescope                                       |
| MOST       | Microvariability and Oscillation of Stars satellite         |
| MRS        | Major Resources Support program (NSERC)                     |
| MSTC       | Microsatellite Science and Technology Centre                |
| MTRC       | Mid-Term Review Committee                                   |
| NAPRA      | North American Program in Radio Astronomy                   |
| NFIRAOS    | Narrow Field Infrared Adaptive Optics System (TMT)          |
| ngCFHT     | Next generation CFHT  |
| NIR        | Near infrared   |
| NIRCam     | Near infrared camera  |
| NIRSpec    | Near infrared spectrograph                                  |
| NOAO       | National Optical Astronomy Observatory                      |
| NRAO       | National Radio Astronomy Observatory                        |
| NRC        | National Research Council of Canada                         |
| NRCan      | Natural Resources Canada                                    |
| NSERC      | Natural Sciences and Engineering Research Council of Canada |
| NSF        | National Science Foundation                                 |
| OCLE-DOCLE | Oort CLOUD Explorer – Dynamic OCCULTation Experiment        |
| ODIN       | Swedish-Canadian sub-mm satellite                           |
| OMI        | One Metre Initiative  |
| OMM        | Observatoire du Mont Mégantic                               |
| ORAN       | Optical Regional Advanced Network                           |
| ORIC       | Okanagan Research and Innovation Centre                     |
| PDF        | Post-doctoral fellow  |
| PEARL      | Polar Environment Atmospheric Research Laboratory           |
| PI         | Perimeter Institute   |
| RQCHP      | Réseau québécois de calcul de haute performance             |
| SciNET     | U. Toronto Scientific Computing Consortium                  |
| SCUBA      | Submillimetre Common User Bolometer Array                   |
| SDSS       | Sloan Digital Sky Survey                                    |
| SETI       | Search for Extraterrestrial Intelligence                    |
| SHARCNET   | Shared Hierarchical Academic Research Computing Network     |
| 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           |
| SPIRE  | Spectral and Photometric Imaging Receiver                |
| SPIROU | Spectro-Polarimètre Infra-Rouge                          |
| SRO    | Strategic Research Opportunity                           |
| SSEP   | Space Sciences Exploration Program                       |
| 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  |
| VISTA  | Visible and IR Survey Telescope for Astronomy            |
| VLA    | Very Large Array   |
| VLBI   | Very Long Baseline Interferometry                        |
| VLOT   | Very Large Optical Telescope                             |
| VLT    | Very Large Telescope (ESO)                               |
| VO     | Virtual Observatory                                      |
| VSOP   | VLBI Space Observatory Programme                         |
| WFIRST | Wide Field Infrared Survey Telescope                     |
| WIDAR  | Wideband Interferometric Digital Architecture            |
| WiMAX  | Worldwide Interoperability for Microwave Access          |
| WMAP   | Wilkinson Microwave Anisotropy Probe                     |
| z      | Redshift (a measure of distance in the Universe)         |

A photograph of Earth from space, showing the horizon and a bright light source in the upper right corner. The Earth's surface is visible, showing clouds and landmasses. The background is a dark, star-filled sky.

*"A time will come when [people] will stretch out their eyes.  
They should see planets like our Earth."*

Christopher Wren

## Introduction

Astronomy has turned our vast world into an infinitesimal speck, unravelled secrets of the Universe in its earliest moments, and taught us that life truly begins in the deepest depths of space. Discoveries about the nature of our world and Universe have shaped our culture in ways so fundamental that they are easily overlooked. In tandem with these discoveries, astronomy has spawned technological advances that improve our quality of life. From the sensors in many digital cameras, to wireless networking, the impact of astronomy is extraordinarily pervasive. Equally importantly, many scientific methods and techniques developed in astronomy find applications elsewhere – medical imaging is but one crucial example.

Astronomy's legacy of knowledge and discovery is growing faster than ever. At the beginning of this century, the revelation of planets orbiting other stars was a breathtaking new development. Today, we know of over one thousand, and more are found almost every week. We have made measurements of the atmospheres of some of these planets and even predicted their weather. In the next ten years, Very Large Optical Telescopes (VLOTs), including the Thirty Meter Telescope (TMT), may make the first measurements of the signatures of life itself on other planets. An answer to the age-old question "Are we alone?" truly beckons.

We have also learned much about the nature and future of our Universe. The mysterious "Dark Energy" which will eventually drive ever faster cosmic expansion, was a new discovery ten years ago. Yet today, despite the decade since its discovery, little is known about its fundamental nature or its evolution. At the end of this decade, new space-based telescopes such as the European Space Agency's (ESA) "Euclid" and radio telescopes like the Square Kilometer

Array (SKA), the most ambitious technological project ever considered in astronomy, will help answer these questions.

As astronomy answers deeper questions, its research tools demand new capabilities and technologies. In response to this challenge, astronomical research has become more collaborative and international. Spectacular new facilities dubbed "World Observatories", of which ALMA, JWST, the TMT and SKA are examples, are destined to lead the way in astronomical research for the foreseeable future. Yet in this new global landscape Canada will play a leading role because Canadian astronomy is, by any measure, outstanding. In standard impact analyses it ranks number 1 in the G8. Remarkably, these results have been achieved despite a notably lower relative investment than other countries. Within Canada, astronomy has a higher world impact than any other science or engineering research area. When compared to other natural sciences the field has also garnered twice as many Canada Research Chairs as would be expected, and received a disproportionately high number of NSERC prize fellowships. Astronomy is as much a true Canadian success story as Olympic gold medals in hockey.

This remarkable achievement has been driven by access to powerful and agile facilities, by a careful selection of science strategies, and through the training of exceptional and talented researchers. In the past decade Canadian astronomers were front and centre in the highly cited "Legacy Surveys" conducted by the Canada-France-Hawaii Telescope (CFHT). Canadians have also pioneered groundbreaking new techniques to directly image extrasolar planets. Contributions to the Atacama Large Millimetre Array (ALMA), the first of the "World Observatories", include the design and building of

the critical "Band 3" receiver cartridges. The Canadian Institute for Theoretical Astrophysics has also cemented its role as a world-leading centre for the study of the Cosmic Microwave Background. In 2003 Canada launched its first ever orbiting space telescope, Microvariability and Oscillations of STars (MOST), and committed to major investment in the James Webb Space Telescope (JWST), the premier next generation space facility. JWST is the successor to the Hubble Space Telescope, and will, for the first time, allow us to detect signals from the very first galaxies in our Universe.

## Priorities for a new decade of discovery

LRP2010 ("the plan") outlines an exciting vision for Canadian astronomy over the next decade which will maintain Canada's position in the upper echelon of international astronomy. LRP2010 is a product of over a year of consultation and discussion with the entire Canadian astronomical community. Equally importantly, the plan is driven by the priorities outlined in the Canadian Government's Science and Technology strategy. Difficult choices relating to the closure of current facilities have been made to free capital for the next generation of facilities. Despite over 50 projects being submitted to the Long Range Plan Panel (LRPP) for consideration, the final document includes recommendations for only 13 new facilities/experiments/missions over a period of 10 years. To put this number in perspective, the Canadian Space Agency (CSA) alone participated in 7 space astronomy missions during the 2000-2010 decade. The selected priorities also ensure Canadian astronomy has access to multiple observational wavelengths, a key part of any comprehensive understanding of physical processes.

The top priority for Canadian astronomy over the coming decade is participation in a VLOT, specifically building on our investment in the development of the TMT and converting our world-leading designs into a constructed facility. As the TMT is reaching completion toward the end of the decade, the SKA is scheduled to begin construction. At that time the SKA will supplant TMT as the top priority for new facilities in Canadian astronomy. In space astronomy, our priorities are involvement in the next generation of “Dark Energy” missions – ESA’s Euclid, or the NASA “WFIRST” mission, or a Canadian-led mission, the Canadian Space Telescope (CST). At X-ray wavelengths, the explosive growth in Canadian high-energy astrophysics puts involvement in the International X-ray Observatory (IXO), at a high priority.

New facilities must be managed in ways to maximize scientific discovery, productivity and accountability; training must efficiently support these goals. The plan thus presents a new proposal for the governance of the Herzberg Institute for Astrophysics (HIA) within the National Research Council (NRC). The envisioned structure will help the NRC maintain its dedication to its core mission while providing a closer tie between management and mission within the HIA. The plan also notes the need for training of a new generation of highly qualified personnel (HQP), capitalizing on the inspiration of students that has always been one of the key benefits of astronomy. Undergraduate participation in research astronomy is growing rapidly and many of the techniques learned during this work will yield

advances outside astronomy. LRP2010 also makes recommendations in support of the development of new technologies, instrumentation laboratories at universities and high performance computing. Through a carefully planned outreach campaign the scientific success and technological benefits of astronomy will be communicated to an interested public. Even without this outreach, many of the new technologies outlined have significant economic ramifications and can help address Canada’s “innovation gap”.

Amortized over a decade, the report calls for approximately \$40M per year of new investment in ground-based facilities. Space-based facility and mission investment is potentially lower than the previous decade by 30 percent, but depends crucially upon involvement in a dark energy mission, and on mission costs that are not yet known. The overall increase in investment would still yield a relative investment in Canadian astronomy below the levels of other nations in the G8.

The layout of this report is as follows: in Chapter 1, we present an overview of Canadian astronomy and summarize the LRP process. In Chapter 2, we outline the spectacular science questions that we hope to address over the coming decade. Existing facilities and institutes are discussed in Chapter 3, followed by proposed new ground-based facility investments in Chapter 4, and space-based missions in Chapter 5. In Chapter 6, we outline some of the challenges faced in governance structure of Canadian astronomy and provide detailed international comparisons

of funding. Demographics are reviewed in Chapter 7, and the broader impact of astronomy in society is discussed in Chapter 8. We summarize recommendations in Chapter 9. Appendices address terms of reference, student training, postdoctoral fellow demographics, international funding, industrial successes, and the findings of a working group that studied Canadian involvement in the European Southern Observatory.

## Concluding Remarks

The LRP Panel acknowledges the support it has received from NRC, NSERC, CSA, CFI, and CIFAR over the past decade, and looks forward to a renewed commitment to astronomy in the next decade of discovery.

A cautionary comment: The information in this report was accurate as of Feb 2011, but is evolving rapidly.







*LRP2010 is a ten 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?***

## Executive Summary

LRP2010 is a ten 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?

Through a careful choice of projects, the plan, authored by the LRP Panel (LRPP), will maximize research breakthroughs and outcomes through training and investment. On a relative impact basis Canadian astronomy is the best in the G8, despite lower investment than other countries as a fraction of GDP. Nationally it has garnered a disproportionately large number of Canada Research Chairs and Natural Sciences and Engineering Research Council (NSERC) prize awards. Equally importantly, astronomy fits well within the Government's Science and Technology strategy "Mobilizing Science and Technology to Canada's Advantage". From its world class excellence, to its wide accountability through public education and outreach, astronomy continues to enrich Canada for all Canadians.

### Astronomy and Canada: A productive partnership

Science is arguably more important to society than ever before. We face great challenges, particularly in the environment and energy sectors, while still needing to ensure economic growth and prosperity for all. Astronomy directly helps address these concerns. From attracting students to science, to the training and education of students, to the creation of new technologies, the influence of astronomy is as wide as it is unexpected.

Astronomy's breadth of appeal, beauty and relevance makes it a superb tool for increasing public understanding of science and technology. This popularity was demonstrated in 2009 with over 1.9 million Canadians participating in events during the International Year of Astronomy. Readership of the Canadian "SkyNews" magazine is estimated to be 80,000 while thousands of Canadians are members of astronomical societies such as the Royal Astronomical Society of Canada and the Fédération des astronomes amateurs du Québec.

The Conference Board of Canada ranks science skills as one of the key contributors to entrepreneurial innovation and technological advancement. Every year tens of thousands of school children, typically in Grades 1,6 and 9, are inspired by the astronomy they learn to investigate the Universe around them. Many scientists and engineers cite this early learning as a key step in their career choice. Moving to the university level, co-op programs in astronomy instrumentation provide students with exposure to both the underlying science and commercial technology aspects. This appears to be a uniquely Canadian asset.

Building on this platform of knowledge and skill development, over 200 Canadian companies are now engaged in astronomy projects. Hundreds of millions of dollars in revenue can be directly traced to technologies developed from astronomical research. Equally impressive is the list of technological advancements resulting from astronomy. Wireless networking, advanced radar for stealth aircraft detection, GPS operation and calibration, X-ray scanners for baggage analysis, "cloud" computing, algorithms for medical imaging and adaptive optics in eye surgery are just a few examples. Indirect returns on investment have even been rated as high as ten-to-one.

LRP2010 will extend this legacy for the benefit of all Canadians. The selected astronomy facilities and missions require new technologies that will foster new product areas and revenue streams for Canadian companies. Information and communication technologies, including both cell phones and radar, will benefit from a new generation of low noise, high efficiency amplifiers and analog to digital converters that are currently being developed for future radio telescopes. New signal processing electronics will stretch the design and manufacturing capabilities of the electronics sector. Structural engineering requirements for new facilities require unprecedented levels of design integration and are already taking Canadian engineering company expertise to new heights. Numerous other technology areas will present Canadian companies with a chance to extend or gain marketplace leadership.

### The Challenges Ahead

As the challenges of astronomy research become greater, and the questions it answers more fundamental, international collaboration is becoming increasingly necessary. Over the next decade five "World Observatories" will either be operational, under construction, or planned: the Atacama Large Millimetre Array (ALMA), James Webb Space Telescope (JWST), Very Large Optical Telescopes (VLOTs, such as the Thirty Meter Telescope (TMT)), Square Kilometer Array (SKA) and International X-ray Observatory (IXO). These facilities, covering wavelengths from radio to X-rays, will provide a transformative picture of astrophysical systems. Supported by more specialist telescopes, these facilities will lead the vanguard of astronomical discoveries for decades.

Canada has made significant contributions to the construction of both ALMA and JWST, the much anticipated follow-on to the Hubble Space Telescope. We have also been heavily involved in the design of TMT and prototyping of SKA technologies. However, at this time funding for our participation in TMT and SKA construction is not assured. Neither is any kind of participation in IXO. Since the TMT consortium hopes to begin construction soon, the window for Canadian involvement, thereby capitalizing on the substantial investment that has been made, is closing.

In the past decade Canadian involvement and capacity in space astronomy has grown spectacularly. The Canadian Space Agency (CSA) managed Canada's participation in seven missions, including the first Canadian space telescope, Microvariability and Oscillations of STars (MOST). Further, through construction of the Fine Guidance System for JWST, Canadian technology will be front and centre every time the telescope is pointed. In the next ten years several missions present exceptional synergies with Canadian research interests and industrial expertise developed over the past decade. Even more ambitiously, Canadian space astronomy technology has reached the point that we could lead a large space astronomy mission (Canadian Space Telescope, CST).

As new facilities are constructed careful thought must be given to the management of existing ones. In some cases closure is a necessity. In others critical science questions may warrant a new mission for a facility, perhaps to focus on surveying the sky. The Canada-France-Hawaii Telescope (CFHT) prospered through application of this strategy. But in the next decade, the future of at least three facilities currently operated by Canada (the James Clerk Maxwell Telescope (JCMT), CFHT and Gemini Observatory) must be considered in the light of others that are currently being built.

As astronomy becomes more collaborative and international in scope, our strategy of operations and capital investment will play an increasingly important role. Astronomy in Canada is funded by the National Research Council (NRC), CSA, NSERC, Canada Foundation for Innovation (CFI) and Canadian Institute for Advanced Research (CIFAR). The NRC operates the Herzberg Institute for Astrophysics (HIA), a de facto national laboratory, to serve its mandated role to "operate and administer astronomical observatories established or maintained by the Government of Canada". However, the recent change in NRC's strategic priorities has created uncertainty within the astronomy community as to whether it will be able to meet the coming needs of the field. This leads to the question of what alternatives exist for the governance, more specifically operations, of the HIA? Such alternatives must also work together with the NRC to the benefit of all stakeholders.

## A Vision for Canadian Astronomy 2010-2020

LRP2000, the first astronomy decadal planning exercise in Canada, became the catalyst behind a new era of investment and scientific breakthroughs. Much has happened in the ten years since 2000: the Gemini telescopes became operational, ALMA is nearly operational, and JWST is approaching a mid-decade launch. Other "World Observatories" are reaching construction readiness, the CFI has improved the funding landscape in Canada, and the astronomy community has grown significantly. Faculty and other permanent appointments now total over 200, graduate students almost 300, and postdoctoral fellows over 100. In the same time period undergraduate involvement in astronomy research has more than doubled, reaching over 150 in 2010.

Ten years later, a new plan for the next decade of discovery is urgently needed; this document is a response to that need. The plan builds around three pillars of astronomy research success: state-of-the-art facilities, highly qualified personnel and operational support. Only if attention is paid to all three of these critical areas will the community prosper and rise to its ultimate potential.

From a list of over 50 telescopes and missions that were proposed as part of the LRP2010 planning process, only 13 telescopes/missions are considered in the final plan. The selected projects, which are separated into ground- and space-based, span a range of wavelengths from radio to X-rays, and a range of scientific goals from the fundamental nature of the cosmos to the search for life on other planets. They also span a range of investment levels from under \$1M to potentially over \$200M. A budget for the plan can be found at the end of this section.

## New ground-based facilities

### *Optical and Near Infrared: TMT*

The single most important project, in the near term, for Canadian astronomy is participation in a Very Large Optical Telescope (VLOT), the Thirty Meter Telescope (TMT). TMT will examine the first galaxies to form in our Universe, help uncover the role of black holes in galaxy evolution, and may even detect the signatures of life in the atmospheres of planets around other stars. Canadian astronomy has led developments in a number of these science areas.

TMT was originally a Canadian-American partnership; it has evolved into a highly international collaboration, with Japan, China and India now either involved or expressing interest. Despite this widening of the collaboration, Canadian investment in the project makes it a founding partner and over \$22M has



been invested in Canada on design work. Dynamic Structures Limited has developed innovative integrated dome and support designs, while Canadian expertise in adaptive optics has seen the HIA lead development of the adaptive optics package.

Scientific returns, protecting investments and ensuring the maximum voice for Canadian interests in the TMT project, underlie the LRPP recommendation that Canada seek involvement in the construction and operation of TMT at a level that is “second-to-none”. At present this represents a 25% stake. If construction proceeds promptly, funds will be needed in the short term to ensure Canada’s participation. (The total cost of TMT – all partners – is estimated to be \$1.2B in 2010 \$.)

However, the LRPP is also concerned about possible delays in TMT. Experience has shown that leadership requires being the first into a new discovery space. The European Southern Observatory is developing the European Extremely Large Telescope (E-ELT), a VLOT with science capabilities similar to those of TMT. If by 2012 delays in TMT have put it significantly behind the E-ELT then the LRPP recommends Canada partner in the E-ELT project and join ESO.

### ***Radio: Towards the SKA***

The SKA is the single most ambitious technological project ever undertaken in astronomy. Relying upon numerical processing to combine radio signals from tens of thousands of high-sensitivity antennas, it has been called an “ICT telescope”. Many of the technologies being developed for the SKA have the potential to be applied in radio, cell phones, radar and wireless networking technologies. The science that SKA will make possible is even more compelling. Among many planned studies, it will probe whether Einstein’s Theory of Relativity is correct, and help astronomers understand the

formation of stars billions of years ago. Furthermore it will be the first radio telescope with sufficient sensitivity to detect signals from other civilizations throughout the galaxy (should they exist). In the view of the LRPP these outstanding prospects make the SKA the top priority for Canadian astronomy once participation in a VLOT is assured.

The SKA is truly international in scope with more than 20 countries planning to share the total cost of approximately \$1.5B. Canada has made significant contributions to technology development as part of the ‘PrepSKA’ project. Further, Canadian R&D into SKA technologies will be necessary over the majority of this decade and the LRPP recommends this be given a high priority. A precise recommendation for overall investments in the construction phase cannot be made until final construction budgets are more fully understood toward the end of the decade. However, a share commensurate with Canada’s GDP would correspond to a 10% stake. At this time construction is anticipated to take a decade to complete.

Preparation of a new generation of researchers and students for the SKA needs to be started now. A fertile training ground for this purpose will be provided by several current and near-future instruments: the Expanded Very Large Array (EVLA), and the two SKA-precursor radio interferometers (ASKAP in Australia and MeerKAT in South Africa, both currently under construction). In this context, LRPP also notes one other proposed radio telescope, the Canadian Hydrogen Intensity Mapping Experiment (CHIME), which stands out as a highly innovative medium scale Canadian project with great potential returns. Specifically, CHIME is designed to measure the distribution of hydrogen gas in the distant Universe; this can be used to measure the evolution of dark energy, the mysterious energy field that governs the expansion of the Universe.

### ***Submillimetre facilities: ALMA and CCAT***

Complementing the SKA but working at shorter wavelengths is the ALMA telescope. The first of the “World Observatories”, it will be completed in 2013. ALMA will help answer key questions about planet formation and the nature of protoplanetary disks, as well as probing the nature of star formation when the Universe was only one sixth its current age. ALMA was the top priority of LRP2000, and Canadian involvement is a great success story. Canadian companies have won a number of key contracts and the HIA has overseen the development of receivers that will play a critical role in the operation and calibration of the facility. Expertise in software development has also been contributed to the analysis software and data archive development. These successes have led the LRPP to recommend that Canada should quickly identify its priorities in future ALMA development.

Because the ALMA telescope has a comparatively small field of view, there is significant scientific room for a new telescope that can survey large fields to complement ALMA. The CCAT telescope, scheduled for completion in 2020, will perform precisely this role. Subject to a technical review, the LRPP strongly recommends involvement in this project due to its strong synergy with the science goals of the Canadian community.

### ***A new development: Arctic Astronomy***

One of the most interesting developments in the last two years is the unexpectedly high potential of the Canadian Arctic for astronomy. The still air of the polar vortex provides exceptional seeing. Initial studies have been tantalizing but further research is needed before any significant recommendations for building telescopes in the 1-4m range can be considered. The LRPP is recommending that funding be provided

for a more detailed investigation of this exciting possibility, and, once completed, a science and technical case for building a medium sized facility can be considered.

## *The future of current ground-based facilities*

While the scientific promise of SCUBA-2 on the JCMT continues to hold interest, at the present time the international partnership that operates the telescope is scheduled to end on March 31st 2012. The funding from Canada's withdrawal will then be used to provide operations support for ALMA. The LRPP reaffirms that commitments to ALMA operations funding take priority over JCMT. Any continuation of JCMT operations must not impact ALMA, and should only be considered after a performance review of SCUBA-2 and the scientific impact of the potentially descope surveys is determined.

The Gemini telescopes are the largest aperture optical facilities in which Canada currently partners and continue to serve the community well. However, many of the science and design goals of Gemini are shared by TMT and E-ELT. Hence, when the next generation of 30m-class telescopes comes online the central capability of the Gemini telescopes will be surpassed. Therefore the LRPP recommends that Canada's participation in the Gemini Observatory be reconsidered once Canadian access to an operational VLOT is assured.

CFHT has been the workhorse of Canadian astronomy for three decades. Transforming the facility starting in the 1990's to conduct large imaging surveys yielded enormous scientific returns: CFHT had the highest average impact factor of all ground-based telescopes in 2007. However, a number of planned facilities will eclipse the capabilities of CFHT by the end of the decade. In the near term

the LRPP supports the new instrumentation projects for CFHT, for which there is a notable window of scientific opportunity. In the longer term, the main advantage of CFHT is its location. The possibility of redevelopment with international partners, potentially up to a 15 metre diameter telescope with wide-field capability (ngCFHT), is an intriguing idea that bears further study. Therefore the LRPP recommends funding initial design studies.

## **New space astronomy missions**

### *Large-scale investment: JWST and Dark Energy*

Turning to space-based facilities, JWST is the single largest space astronomy project to which Canada has contributed. Delivery of the Fine Guidance Sensor and the Tunable Filter Imager to NASA is scheduled for 2011. However at this time a launch delay appears likely. Therefore the LRPP recommends that the CSA should allocate resources to encompass the costs inherent in this delay.

The question of dark energy evolution binds particle physics and astronomy together. Determining the nature of this energy is one of the most outstanding questions in particle physics, while it has an equally profound impact on the expansion of the Universe. Consequently, dark energy is garnering global interest as a challenge for the coming decade and beyond. Two space-based all-sky imaging missions, Euclid and the Wide Field Infrared Survey Telescope (WFIRST), projects that cost on the order of \$1B, will attempt to measure dark energy evolution using the positions and shapes of galaxies. Such all-sky surveys have many secondary benefits related to understanding galactic structure and evolution. They also complement the next generation of ground-based facilities that will typically have a much smaller field of view. The WFIRST mission was ranked first in the

Astro2010 paper, but recently NASA has stated a desire to enter the Euclid mission. Given Canada's contributions to the study of dark energy and expertise in wide-field imaging, significant involvement in one of these missions is viewed by the LRPP as the number one priority for space astronomy over the coming decade.

In the event that participation in either Euclid or WFIRST is not possible, then the LRPP recommends exploring the possibility of a Canadian-led imaging satellite (CST) focusing on UV-visible wavelengths, as a complement to WFIRST/Euclid. Leading such a project would break new ground for Canadian space astronomy and present numerous opportunities for Canadian companies to showcase technological capabilities.

### *Mid-scale investment: IXO and SPICA*

Perhaps even more ambitious than either of these dark energy missions is the space-based IXO. The global X-ray astrophysics community has come together on this project and as the fifth "World Observatory" it will provide an order of magnitude improvement over current X-ray telescopes. Probing questions about the nature of black holes, ultra-dense matter in neutron stars, galaxy clusters, and the intergalactic medium, it will revolutionize our knowledge of the high energy Universe. The outstanding scientific promise of this mission, and the many areas of technological advancement that it will require, have led the LRPP to recommend R&D involvement in IXO as the number one medium-scale priority for space astronomy. Many avenues for participation are potentially open, including building upon expertise gained from involvement in the Astro-H metrology system.

The Herschel mission, in which Canada made notable contributions to both the SPIRE and HIFI instruments, is an

outstanding success and has shed new light on the Universe at infrared wavelengths. However, the mission lifetime is short, 3.5 years. Current plans call for a vastly more capable mission – the Space Infrared Telescope for Cosmology and Astrophysics (SPICA), led by the Japanese space agency JAXA, and planned for the end of the decade. Unlike Herschel, SPICA will actively cool the mirror in the telescope and thus will achieve over a 100-fold improvement in sensitivity in some wavebands, enabling detailed analysis of objects that Herschel can barely detect as well as finding objects that are beyond Herschel's sensitivity limit. The LRPP thus recommends that Canadian participation in SPICA be given a high priority for medium scale space-based projects.

### ***Astro-H, Micro/nanosatellite and Balloon Missions***

Canada's direct involvement in the development of the metrology system for the Astro-H X-ray telescope will present a host of new opportunities for the high energy astrophysics community. Aside from the notable capacity building and the development of technology skills ready for involvement in IXO, the mission itself will open a new window on the Universe. Astro-H will enable the first combined imaging and spectroscopic observations in the so-called "hard" X-ray band, provide extremely high energy resolution spectroscopic observations, and also make the most sensitive wide-band observations of X-rays to date. Equally important, given that Astro-H is a Japanese-led project, is the building of a new international collaboration with the Japanese Aerospace Exploration Agency (JAXA).

Canada continues to be a world leader in micro- and nano-satellite technology. The Microvariability and Oscillations of Stars (MOST) telescope, and its follow-on Near Earth Object Surveillance Satellite (NEOSSat), are examples of small

satellites that nonetheless produce large science returns. Equally importantly, they can serve as testing grounds for new technologies, the key goal of the CSA's Flight for Advancement of Science and Technology (FAST) program. New applications for this technology include studies of stellar structure and the nature of the outer solar system. The LRPP strongly supports this program as a cost-effective way of answering tightly focused science questions.

Canada has also developed significant expertise in balloon-borne technologies, having participated in the Large-Aperture Sub-millimeter Telescope (BLAST) mission, while currently contributing to the E & B Experiment (EBEX) designed to measure the polarization of the Cosmic Microwave Background (CMB). Such projects continue to yield excellent price performance and can serve as test-beds for new technologies later adopted in space-based missions (the Planck satellite, currently taking the most accurate measurements of the CMB ever made, uses technologies first deployed on balloon missions). A number of upcoming balloon missions, including EBEX and SPIDER, will make detailed polarization maps of the CMB, a science area in which Canada continues to be a world-leader. The continued support of these missions is essential because of their scientific potential, cost effectiveness and their promise for technology development.

### **Personnel, infrastructure and accountability**

The facilities outlined above will provide Canadian researchers with a balanced set of facilities and technologies. Maximizing their use requires that researchers and students be well prepared and funded, especially when the facilities first come on line. The LRPP recommends both that NSERC fund 10 prize fellowships

for PDFs (akin to the US Hubble Fellowships), and that the CSA ensure the SSEP program set aside funds to support 4 PDFs to be involved in JWST (and other mission) data analysis.

To provide theoretical support for these observational programs the LRPP also recommends an increase in the CITA MRS grant to add four additional awards per year in the CITA National Fellows PDF program.

In support of technology development for these new facilities, the LRPP again reiterates the need for adequate funding of experimental astrophysics laboratories in Canada. While some progress has been made in this area since 2000, renewable funding sources are still not available and capabilities, once established, risk being lost in this funding environment. The LRPP also encourages NRC to support Industrial Chairs at Canadian universities.

Equally importantly the LRPP is concerned that computing infrastructure, as funded through Compute Canada (CC), will not meet the needs of astronomy researchers in the next decade. To analyze petabytes of data, petaflops of computing are required. This lack of resources is a critical concern for the CADC, which plays a pivotal role in Canadian astronomy by providing archived data and advanced data products to the community, as it transitions to a reliance on CC hardware. Thus the LRPP strongly recommends an increase in funding to CC comparable to that of other countries in the G8. The LRPP also reiterates the need for a Canadian data management policy. As data volumes continue to grow it is important to the future planning of the CADC to establish how these will be managed.

The LRPP also investigated the broader impact of astronomy. Because research is tax-payer funded astronomers have a duty to communicate and educate the public



about their research. The notable lack of science coverage in popular media means that scientists must make an effort to communicate in this sphere more effectively. Canadian astronomy does not yet have a significant “brand” profile with the Canadian public. As a first step, the LRPP recommends that graduate programs add an outreach component to their degree requirements. On the back of a carefully constructed communications strategy there is potential for an “AstronomyCanada.ca” website, but it will require significant financial support. In support of all these issues, the LRPP thus recommends that funding agencies apportion 1.5% of funds for new facilities to public outreach.

## Governance and implementation of the LRP

LRP2010 recommends a new vision for the management of the HIA. Following the “government-owned, contractor-operated” model used highly successfully in the US, the LRPP recommends that NRC and ACURA negotiate a cooperative agreement to manage the HIA. Such an agreement would directly preserve the NRC’s mandated role to operate and administer the observatories established or managed by the Federal Government. The CSA should also be involved in this new management plan so as to ensure a more integrated and synergistic approach to the development of space astronomy instrumentation. The benefit to the university-based research community is also clear: a new and significant voice in managing Canadian facilities. Combining management and mission directly should have clear benefits for all parties.

During the development of LRP2010 it has become clear that many of the large international projects have not determined partnership levels and in some cases an immediate path forward is not

clear. Equally noteworthy, medium- to small-scale projects can develop on a much shorter time scale than a decade. Clearly some flexibility in the LRP is a necessity. The LRPP thus recommends that an Implementation Committee (LRPIC) be formed to carry through the mandate of the planning process.

## Canadian Astronomy in 2020

How will a successful outcome of LRP2010 be measured? This apparently simple question spans issues from scientific discovery and innovation through to training and socioeconomic benefits. How many of our key science questions stand to be answered by facilities that will come on line in the next 10 years? Will the community be ready for the facilities that are constructed at the beginning of the 2020s, such as the SKA? And, perhaps most significantly, will Canadian astronomy have maintained the international position and reputation that it has earned over the past four decades?

Assuming projects evolve in a timely manner, the picture that emerges for the future is truly exciting. By 2020 the ALMA telescope will have had six years of operation. JWST will have been in operation for four years and TMT for two years. Phase 1 of the SKA will be either starting or close to completion. ALMA will have provided detailed observations to help us understand the formation and evolution of protoplanetary disks. JWST and TMT will have observed the first stars and galaxies, Euclid/WFIRST/CST will be placing detailed constraints on dark energy evolution. We will have a new found understanding of the formation of stars and how this process changes with cosmic time. Many new worlds around other stars will have been found. The breakthroughs will have opened a new window on the nature of the Universe.

But more importantly, Canadians will have led a significant fraction of this research. International collaborations will have been nurtured. The next generation of students and PhDs will be relying on newly developed analysis tools and technologies. The extensive growth in undergraduate involvement in research will have continued and blossomed. Some undergraduates will have taken skills developed in astronomy into different fields.

If technology development plans are executed, we can expect to see application of new technologies in many different areas. Signal processing boards required for both TMT and the SKA will have pushed Canadian integrated circuit board technologies to new heights, just as the WIDAR correlator did for the EVLA. Low power, low noise amplifiers, analog-to-digital converters and phased-array detectors developed for the SKA will likely be finding applications in cell phones and RADAR, within both commercial and defense sectors. New composite material manufacturing techniques will be breaking price-performance barriers in the design of antenna structures. Innovative engineering developed for the TMT dome will have found application in other areas of structural engineering. Algorithms developed for data analysis and simulations on petascale supercomputers will find applications in areas from medical imaging to fluid dynamics. All Canadians stand to benefit, either directly or indirectly, from these advances.

But the history of astronomy, and science generally, tells us that the most startling discoveries are unanticipated. For all the science questions the next ten years will address, the truly unknown captivates just as strongly. Unveiling the cosmos will reveal wonders we have yet to imagine.



## New Funding for Astronomy 2010-2020

See §9 for a detailed description of this budget. At the time of writing, funding levels for several space facilities are being determined.

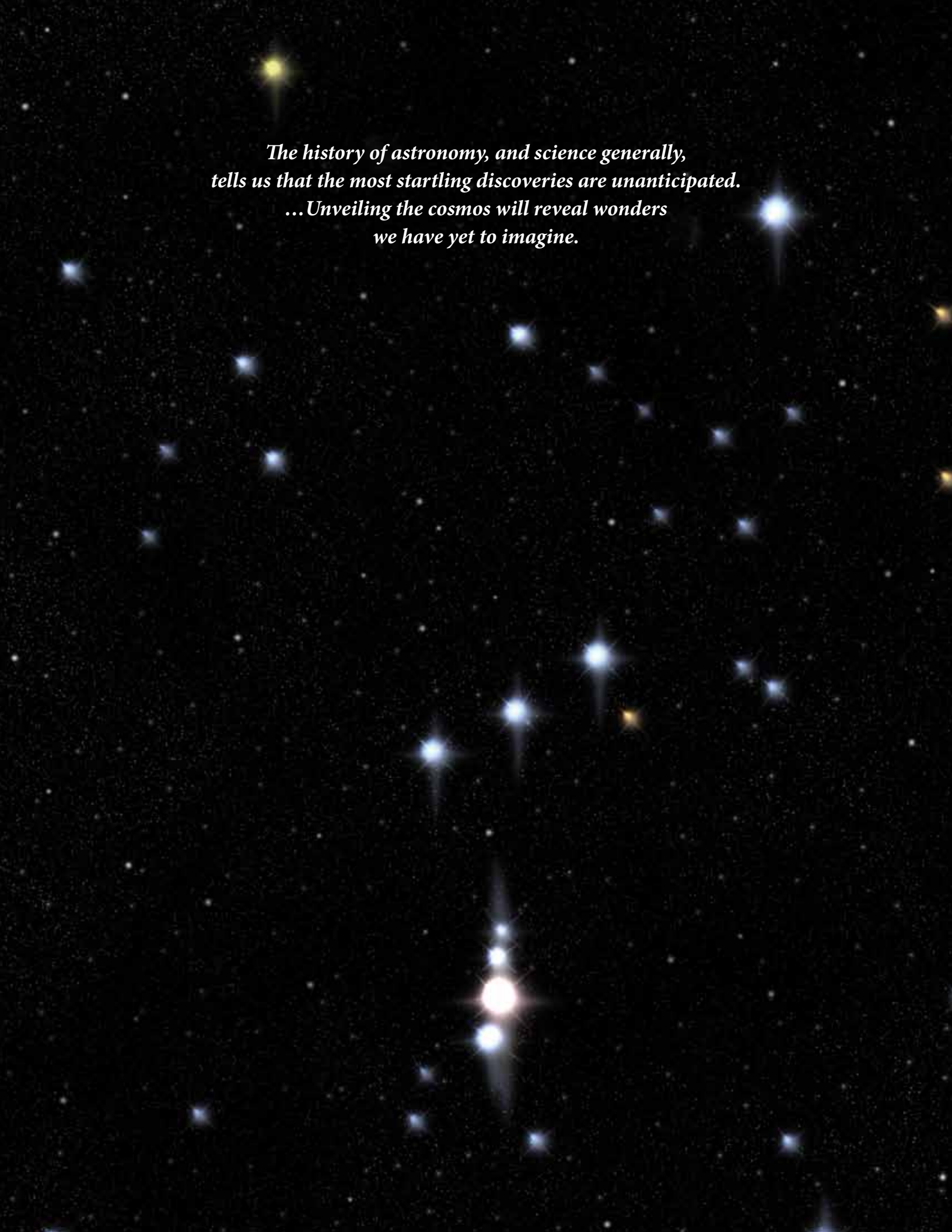
|                 | <i>Category</i>           | <i>Priority</i> | <i>Project</i>           | <i>\$</i>     |
|-----------------|---------------------------|-----------------|--------------------------|---------------|
| <b>GROUND</b>   | Very Large (above \$100M) | 1               | VLOT                     | \$305M        |
|                 | Large                     | 1               | SKA                      | \$60M         |
|                 | Medium (\$5M-30M)         | 1               | CHIME                    | \$15M         |
|                 |                           | 2               | CFHT new instrumentation | \$5M          |
|                 |                           | 3               | CCAT                     | \$15M         |
|                 | Small (below \$5M)        | 1               | Arctic                   | \$4M          |
|                 |                           | 2               | ngCFHT                   | \$2M          |
| <b>Subtotal</b> |                           |                 |                          | <b>\$406M</b> |

|          |        |   |                   |        |
|----------|--------|---|-------------------|--------|
| SPACE    | Large  |   | Euclid/WFIRST/CST | \$100M |
|          | Medium | 1 | IXO               | \$15M  |
|          |        | 2 | SPICA             | \$10M  |
|          | Small  |   | Astro-H           | \$5M   |
|          |        |   | Balloon           | \$5M   |
|          |        |   | Microsatellite    | \$5M   |
| Subtotal |        |   |                   | \$140M |

|                               |       |         |
|-------------------------------|-------|---------|
| <b>Infrastructure, People</b> | PDF's | \$11.3M |
|                               | Labs  | \$32.5M |

|              |               |
|--------------|---------------|
| <b>TOTAL</b> | <b>\$590M</b> |
|--------------|---------------|

|              |          |  |
|--------------|----------|--|
| <b>OTHER</b> | Outreach | 1.5% of new project funding for Astronomy (all agencies) |
|              | HPC      | \$30M/yr new funds for all Canadian HPC users            |

A deep space photograph showing a vast field of stars against a black background. The stars vary in brightness and color, with some appearing as sharp points of light and others as larger, more diffuse clouds. The overall composition is centered, with the text overlaid in the upper half.

*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.*

# 1. Overview of the LRP Process

## 1.1 Overview of Canadian Astronomy

Astronomy provides answers to some of the grandest questions about the Universe and our place in it: How did the Universe materialize and how is it evolving? How do planets, stars, and galaxies form? Is there life elsewhere in the Universe? For the past century, Canadian astronomers have been intimately involved in seeking answers to these and other fundamental questions that have perplexed humanity since the dawn of time. Moreover, in their quest to understand the Universe, astronomers have driven dramatic technological innovation and stimulated economic growth.

The Canadian astronomical community comprises approximately 200 faculty members or equivalent, 100 post-doctoral fellows, and 300 graduate students (see §7.1). These numbers have been growing rapidly: faculty numbers have grown by 70% in the past decade, and the number of PhD's from Canadian universities has almost doubled in the same period. The bulk (more than 90%) of astronomy research in Canada takes place at universities; of this research, approximately 2/3 is of an observational nature, and 1/3 is theory.

The Canadian astronomical community has an excellent reputation (see §2.3). Space Science and Astronomy is the highest ranked of all Canadian sciences in terms of international impact over the 2005-2009 period. Furthermore, Canada has a higher impact in international astronomy than any of the G7 nations; this is in spite of a lower astronomy investment per GDP than almost any other industrialized country (§6.2).

The National Research Council (NRC) plays a crucial and unique role in

Canadian Astronomy. The mandate of NRC explicitly includes stewardship of Canada's national astronomical observatories – both the Observatories operated under international partnership agreements, as well as the domestic telescopes operated by NRC-HIA. The international telescopes in which Canada has a share are the Canada-France-Hawaii Telescope (CFHT), Gemini Observatory, the James Clerk Maxwell Telescope (JCMT), and, in the future, the Atacama Large Millimetre Array (ALMA). NRC also operates the Herzberg Institute of Astrophysics (HIA), which effectively acts as a national laboratory for Canadian astronomy (§3.3.1). Other smaller telescopes and experimental laboratories play a key role in training and skill development in Canadian astronomy (§3.3.3).

The Canadian Space Agency (CSA) also plays a critical role in Canadian astronomy (§§5 and 6.4.3). CSA has funded important components of many astronomical satellites, including the James Webb Space Telescope (JWST, scheduled 2015 launch), the much-anticipated successor to the Hubble Space Telescope.

The Canadian Institute for Theoretical Astrophysics (CITA) is a national institute that is unique in its vision and that remains highly successful. Hosted at U. Toronto, it is one of the premier astronomy theory centres in the world. Other strong theory groups exist at several Canadian universities.

The funding landscape for Astronomy is complex and multifaceted (§6). Total (operational plus capital) funding is approximately \$100M (\$70M excluding salaries) in 2010, with contributions from NRC (overseas telescopes and HIA), NSERC, CFI, CSA (space astronomy, especially JWST instrument construction, which comprises half of the 2010 total),

and CIFAR, and indirect contributions from other government agencies such as CANARIE and NRCan.

A critical component of Canadian astronomy is the involvement of industrial partners in its activities. Astronomy by its very nature drives technical innovation, ranging from structural engineering on very large scales, down to development of sensitive devices for detecting light across the electromagnetic spectrum. §8.2 discusses the economic impact of astronomy, and shows how investment in astronomical research is well aligned with Canada's national priorities in science and technology. Appendix F highlights a selection of Canadian companies involved in Astronomy to illustrate the innovation Astronomy has brought to their business development.

Astronomy is an exceptionally dynamic discipline, with rapidly evolving science priorities and needs for facilities. For Canadian astronomy to maintain its excellence, it is therefore essential that we re-examine priorities on a regular timescale. This leads us to a discussion of the Long Range Plan (LRP) process.

## 1.2 LRP2000 and MTR2005

The Long Range Plan 2000 came into being at a time when several new facilities and programs were being proposed, and stemmed from a desire by NRC, NSERC, and the Canadian Astronomical Society (CASCA) to coordinate efforts during a time of great change in, and stress on, the funding landscape. The LRP2000 Panel (chaired by Ralph Pudritz, McMaster U.) was commissioned by the agencies, with the full participation of CASCA; this panel met during 1998-99, and issued

a report<sup>1</sup> that coherently prioritized facilities and programs in the decade 2000-2010, with a forward look to 2015. The LRP2000 report also addressed issues related to human resources and outreach. In brief, LRP2000 recommended our participation in the construction of ALMA and the James Webb Space Telescope (JWST), and argued for funding for development work in a Very Large Optical Telescope (VLOT) and in the Square Kilometre Array (SKA).

Following an LRP2000 recommendation, a Midterm Review (MTR) Committee was struck in 2005 by CASCA, funded by NRC-HIA and NSERC, to assess the progress of the LRP, and issue a report<sup>2</sup> with recommendations to ensure that the LRP2000 achieved its goals.

### LRP2000 – How did we do?

LRP2000 was approved “in principle” by the Government of Canada in 2001, and approximately \$300M of new funding has flowed to astronomy since then. Of this, nearly two thirds is from CSA for participation in JWST, Herschel and Planck space missions (§3.2). Close to \$70M of LRP funding has been provided through NRC since 2002 for ground-based astronomy, but it should be emphasized that no new funding has been allocated to NRC by the Government of Canada specifically for the LRP subsequent to the federal budget of 2003.

On the positive side, ALMA construction is nearly completed, and ALMA is due to start early science observations in late 2011. Canada’s participation in JWST has been funded through CSA; Canadian involvement in the development of a VLOT (TMT) and SKA R&D has also been funded. (§ 4.1.1 and 4.1.2 for further details on the recent evolution of these projects.)

## 1.3 Changes in Landscape over the Past Decade

Since the release of LRP2000, a number of changes have occurred that will directly affect the development of astronomy post-2010.

### *New Ground-Based Facilities*

The Gemini telescopes went into operation in 2000 and 2002, and now urgently need a new generation of instrumentation. As discussed above, ALMA was funded, and is approaching completion (2013).

### *Future World Observatories*

TMT is ready for construction, and SKA will be by the end of the decade. Uncertainties in the TMT funding process in the US have resulted in Canada seriously assessing another VLOT project (the European E-ELT).

### *Space Astronomy*

CSA has emerged as a major player in Canadian astronomy. Herschel and Planck were launched in 2009, and appear to be an outstanding success. Canadian participation in JWST was funded; JWST is on-track for a 2015 launch.

### *Agencies and Organizations*

CFI was created, and now funds, along with its partners, a significant portion of new astronomical facilities and instruments under \$20M. The Association of Canadian Universities for Research in Astronomy (ACURA) was formed, and is playing a major role in our participation in TMT.

### *Human Resources*

Astronomy faculty numbers have grown by 70% since 2000, and post-doctoral fellows and graduate students by a factor of two. Over the past decade, Canada has developed a significant research presence in High Energy Astrophysics, Planetary Astrophysics, and Instrumentation.

### *Changes at NRC-HIA*

HIA has evolved towards a “National Laboratory” that serves Canadian Astronomy. NRC, within which HIA is embedded, has evolved further away from supporting pure science. As a consequence, governance issues have arisen that need to be addressed.

All of these bullets are discussed elsewhere in the report in detail. With these points in mind, we now turn to LRP2010.

<sup>1</sup> “The Origins of Structure in the Universe: Canadian Astronomy and Astrophysics in the 21st Century”, <http://www.casca.ca/lrp/front-back/en-index.html>

<sup>2</sup> “The Origins of Structure in the Universe: Mid-Term Review”, [http://www.casca.ca/lrp/mtr\\_approved.pdf](http://www.casca.ca/lrp/mtr_approved.pdf)



## 1.4 LRP2010

LRP2010 was commissioned by CASCA in 2009, with the support and cooperation of ACURA, NSERC, NRC, CSA, and CFI. (The participation of all relevant agencies in LRP2010 is a development with respect to LRP2000 that Canadian astronomers welcome.) The Terms of Reference of LRP2010 are found in Appendix A.1, and the membership of the LRP Panel (LRPP) is found in Appendix A.2. To quote from the Statement of Task in the Terms of Reference:

*“The panel will review the field of space and ground-based astronomy and astrophysics. Both current and future scientific goals and the various needs of the different Canadian communities in astronomy and astrophysics will be considered. From this review the author panel will then produce a list of recommended priorities for the next decade, to be outlined within LRP2010. These priorities will only include those considered to be essential to the success of the Canadian astronomical community. The resulting plan will serve as a single unified vision for highest priority projects in astronomy in Canada over the coming decade.”*

The process by which the LRPP met and gathered information is described in Appendix A.3. An important component of the information gathering was the request for commissioned and contributed White Papers covering all facets of Canadian Astronomy. These White Papers will remain online<sup>3</sup>, and are an invaluable supplemental source of information for this report.

## 1.5 Relationship with the US and European Long-Term Plans for Astronomy

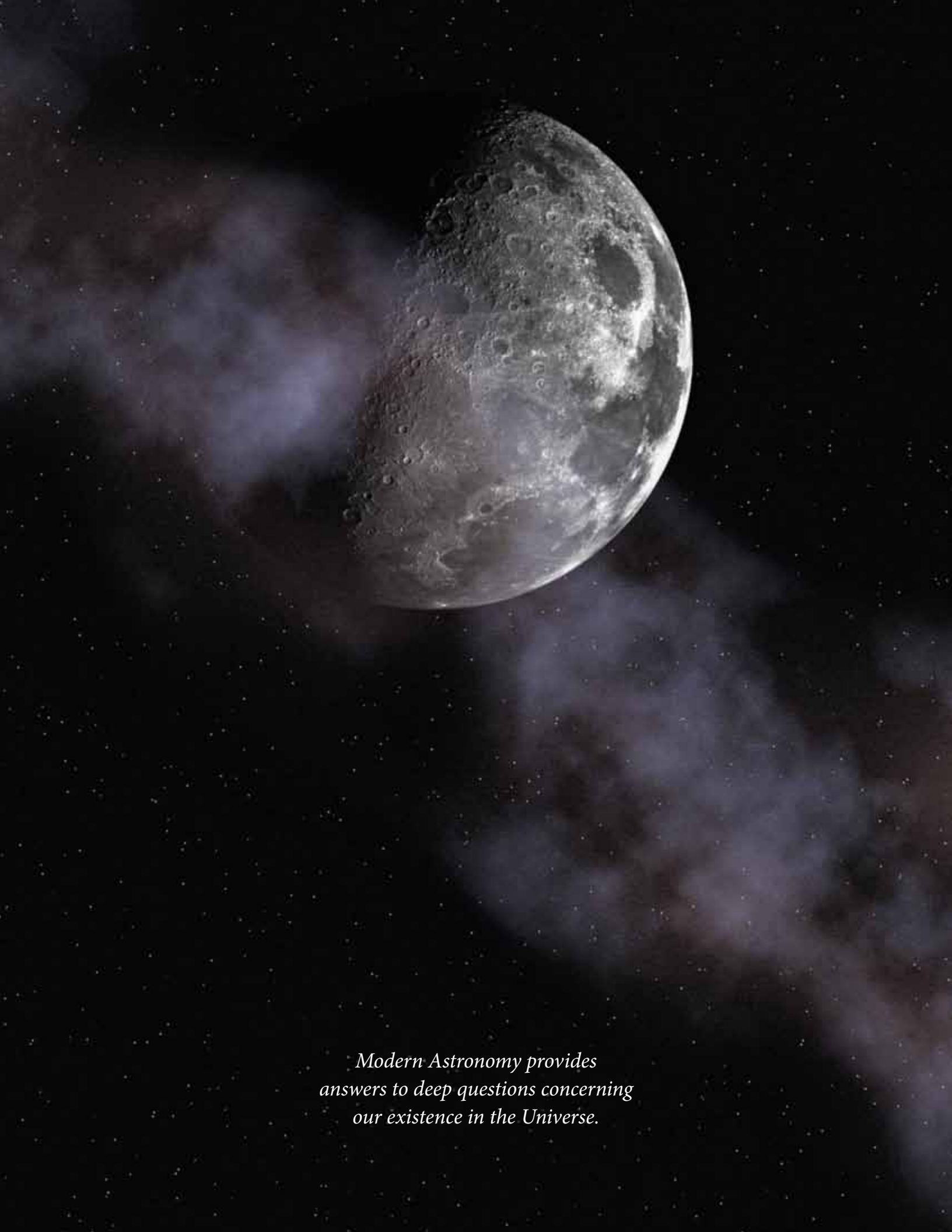
The US Decadal Survey has issued a Report<sup>4</sup>, widely known as Astro2010, that summarizes priorities for US astronomy 2010-2020. In Europe a 20-year planning exercise was undertaken during 2006-2008, and the resultant ASTRONET document summarizes European priorities from 2010-2030. Although the timescales are somewhat different, both plans consider many similar science goals and facilities. Even so, the two plans exhibit differences in priorities. As might be expected, being reflective of the interest of Canadian astronomers, LRP2010 shares differences and similarities with these two reports.

For example, we agree that participation in a Dark Energy satellite mission (NASA's WFIRST or ESA's Euclid or Canada's CST) is the highest priority new large-scale mission for space astronomy over the next decade (§5.1, subject to several caveats). On the other hand access to a VLOT remains of pivotal importance in Canada (§4.1.1), but was assessed at number 3 priority for large ground-based projects in the US (behind the Large Synoptic Survey Telescope, LSST, which is not prioritized in Canada's LRP). In ASTRONET, a VLOT emerged as joint top priority along with the Square Kilometre Array (SKA), yet Astro2010 did not rank the SKA among its large ground-based projects. LRP2010, however, also considers the SKA to be of very high priority. Finally, the proposed evolution of the Gemini partnership in Astro2010 is a cause for concern in Canada, as explained in §3.1.2.

The differences between LRP2010 and the two other major reports are reflective of Canadian strengths and priorities. The current investment in TMT and SKA development also mirrors the needs and desires of Canadian astronomy. While the different sizes of the communities plays a role, Canada has usually chosen to be involved in a small number of facilities that nonetheless maximizes flexibility and science output.

<sup>3</sup> The LRP2010 website (<http://casca.ca/lrp2010/>) contains a link to these White Papers.

<sup>4</sup> “New Worlds, New Horizons in Astronomy and Astrophysics”, hereafter Astro2010. See [http://sites.nationalacademies.org/bpa/BPA\\_049810](http://sites.nationalacademies.org/bpa/BPA_049810)



*Modern Astronomy provides  
answers to deep questions concerning  
our existence in the Universe.*

## 2. Science

### 2.1 An Overview of Astronomy and Astrophysics in 2010

Modern Astronomy provides answers to deep questions concerning our existence in the Universe. These questions can broadly speaking be grouped as follows:

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

Each of these is considered in turn below.

#### 1. Where did it all come from?

The Universe expanded rapidly from an extraordinarily hot and dense state billions of years ago; this central tenet of modern cosmology is called the “Hot Big Bang”. The Big Bang model is consistent with a variety of observations, including the expansion of the Universe discovered by Edwin Hubble in the 1920s, the abundance of light elements in the Universe, and the bright “echo” of the hot Big Bang, which is seen as microwave background radiation that floods our sky.

In essence cosmology seeks to understand our physical world – the nature of space, time, and matter, and the origins of the fundamental forces that dominate our existence. Yet many fundamental questions remain to be answered in cosmology.

What was the nature and behaviour of the Universe during its earliest moments? What are the parameters that control the expansion and evolution of the Universe, and how are they set? What is the nature of the dark matter that fills the Universe? Why is the expansion of

the Universe accelerating, and what exactly is the mysterious “dark energy” that dominates the dynamics of the Universe and causes this acceleration? This latter question is perhaps one of the greatest questions in all of modern physics.

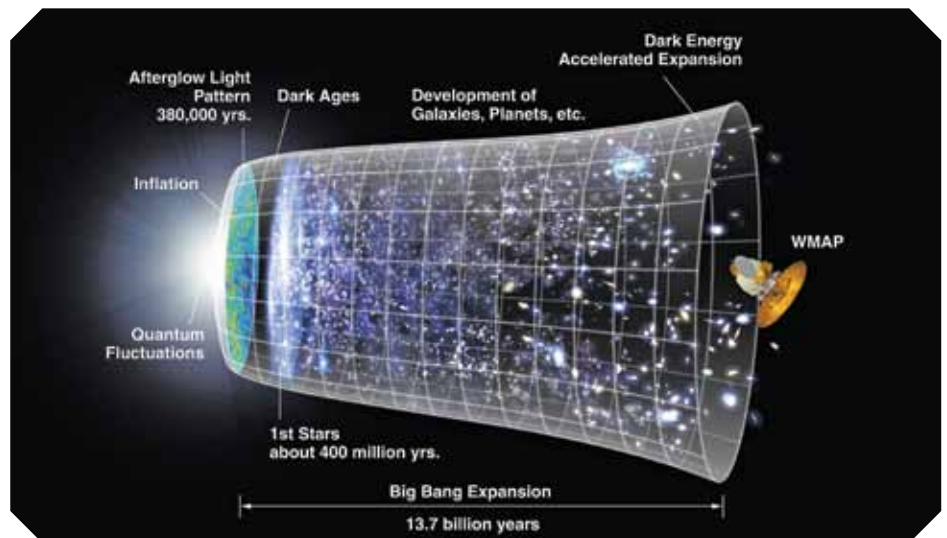


Figure 2-1. The evolution of the Universe from the Big Bang to the present day era. The time axis is not to scale. [NASA/WMAP Science Team]



Figure 2-2. A massive cluster of galaxies in the constellation Draco at a distance of 2 billion light years. The mass of this cluster is greater than  $10^{14}$  solar masses. The prominent arcs superimposed on this cluster are distant galaxies (billions of light years away), which are gravitationally lensed by the extraordinary mass of the cluster. [NASA, A. Fruchter and the ERO Team, STScI, ST-ECF]



## 2. How did it all form?

The Universe is filled with material objects on a phenomenal, almost incomprehensible, range of scales, from planets ( $10^4$ - $10^5$  km in size), to stars ( $10^6$ - $10^9$  km), to galaxies ( $10^{16}$ - $10^{18}$  km), to clusters and super-clusters of galaxies ( $10^{19}$ - $10^{20}$  km). How did this diversity of form come to pass in a Universe that was smooth and nearly featureless after the hot Big Bang? This is one of the broadest and most illuminating questions underlying all of modern astrophysics; the answer is extraordinarily difficult.

Galaxy formation, evolution, and clustering represent complex problems

with a multitude of physical processes at play, and to which Canadians have contributed significantly through observational and theoretical studies. Galaxies must have condensed out of small irregularities in the gas emerging from the Big Bang, but the exact roles of different physical processes remain under intense debate. Because of the finite speed of light, powerful telescopes can be used as “time machines” to peer back to eras less than a billion years after the Big Bang, when galaxies were significantly different from the present day. Advances in computer and networking technology have enabled massive simulations of galaxy formation, and have revolutionized our understanding of galaxy evolution.

The formation and evolution of stars also represents an enormous field of endeavour in Canadian science. Although we have a crude model of how stars form from collapsing gas clouds, the complexity of the physics involved renders this problem formidable at best. The next decade of new telescopes and computer simulations will play a critical role in informing our understanding of star formation. Great strides have been made in understanding the evolution of stars over the past decade; yet there are still many important aspects of the late stages of stellar evolution – e.g. supernova explosions, white dwarf and neutron star formation – that remain poorly understood.



Figure 2-3. (Left) A star forming region in the Milky Way (Messier 20), imaged by the Canada-France-Hawaii Telescope [Canada-France-Hawaii Telescope & Coelum]. (Middle) The massive star eta Carinae, in its final stages of evolution. [NASA and J. Morse, U. Colorado] (Right) The Crab Nebula, a remnant of a supernova explosion in AD 1054 that was observed both by Chinese astronomers and also possibly by Native American peoples in New Mexico. [Canada-France-Hawaii Telescope & Coelum]



### 3. How does it all work?

Astronomy involves physical extremes that are unparalleled elsewhere in science. Nature's ability to create objects of astonishing energy and violence has time and again defied human imagination, and stimulated increased comprehension. By attempting to model the observed behaviour of some of the Universe's most bizarre phenomena – from the powerful jets emitted by the super-massive black holes in the centres of active galaxies, to the huge X-ray and soft gamma-ray radiation emitted in bursts from magnetars – we seek to push our understanding of the laws of physics well beyond what can currently be tested in Terrestrial laboratories, thereby turning the cosmos into a vast laboratory for studying physics in the extreme. In turn, with physical understanding comes insight into the origin and evolution of these remarkable objects, clarifying their place in the Universe.

Specifically at our disposal are astronomical objects that embody extremes of gravitation, energy, density, temperature, and magnetic field. The early Universe may be the Mother of all extreme environments, but its remoteness makes it a challenging specimen; by contrast, in our own backyard are a bevy of bewildering beasts that beg interpretation:

- How could a gamma ray burst billions of light years away reach naked-eye brightness here on Earth? Such an object would have to possess an isotropic luminosity greater than  $10^{15}$  (one million billion) Suns!
- How do certain super-massive black holes spew vast hyper-collimated jets of particles into the intergalactic medium, and why do only some choose to do so?
- Cosmic rays have been detected with energies greater than  $10^{20}$  electron volts – a subatomic particle with a kinetic energy comparable to that of a tennis ball. What mechanism could accelerate elementary particles to such energies?
- What is the nature of matter at densities upwards of 10 times that in the atomic nucleus, such as is believed to exist in the cores of neutron stars?



Figure 2-4. The nucleus of the radio galaxy M87 (NGC 4486), the most luminous galaxy in the Virgo cluster of galaxies at a distance of 60 million light years. The nucleus is centred on a super-massive black hole (mass greater than a billion solar masses). The radio and optical jet, and the radio source itself, are powered by the black hole. [NASA and the Hubble Heritage Team (STScI/AURA)]

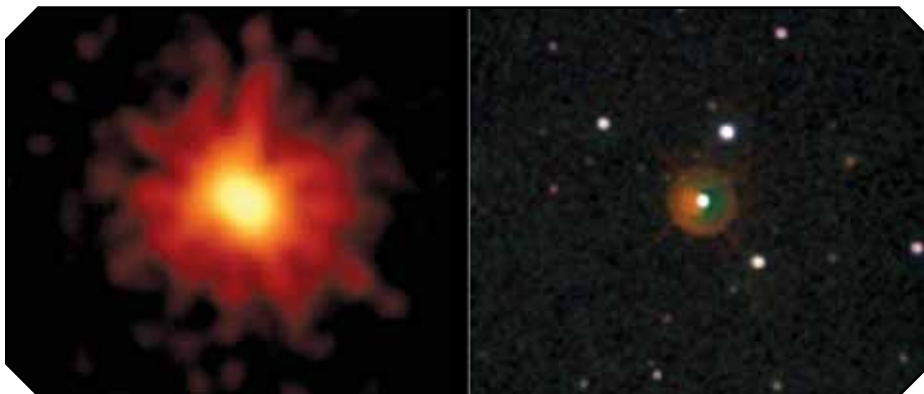


Figure 2-5. Gamma ray burst GRB 080319B at a redshift of 0.94. The extremely luminous afterglow of this GRB was imaged by Swift's X-ray Telescope (left) and Optical/Ultraviolet Telescope (right). This object briefly reached a luminosity of about  $10^{42}$  Watts (approximately  $10^{16}$  times the luminosity of the Sun). [NASA/Swift/Stefan Immler et al.]

#### 4. Are we alone?

For millennia people have speculated that we are not alone in the Universe. More than 2,500 years ago, the Greek philosophers Thales and Anaximander postulated that intelligent beings inhabit planets around other stars, and Giordano Bruno was burned at the stake only four centuries ago, in part for holding such beliefs.

What would the discovery of intelligent life elsewhere in the Universe mean for humans? Such a discovery has the potential to revolutionize society. The detection of life elsewhere in the Universe is a far-reaching goal of modern science, involving all of the natural sciences – from biology to astrophysics. The detection of extraterrestrial life would lead to an understanding of how life originated on Earth, and under what conditions it could evolve on other planets.

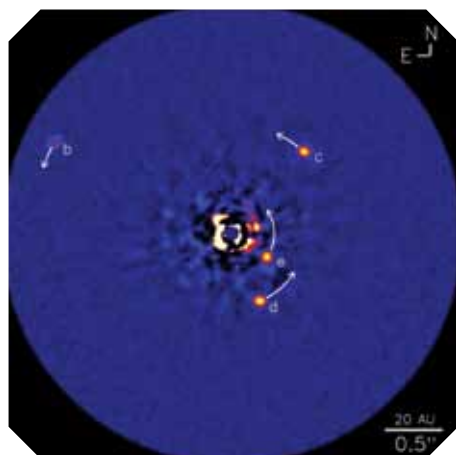


Figure 2-6. Direct detection of 4 planets orbiting the nearby star HR8799. This work was a result of observations by a team led by Canadian astronomer Christian Marois. [NRC-HIA, C. Marois & Keck Observatory]

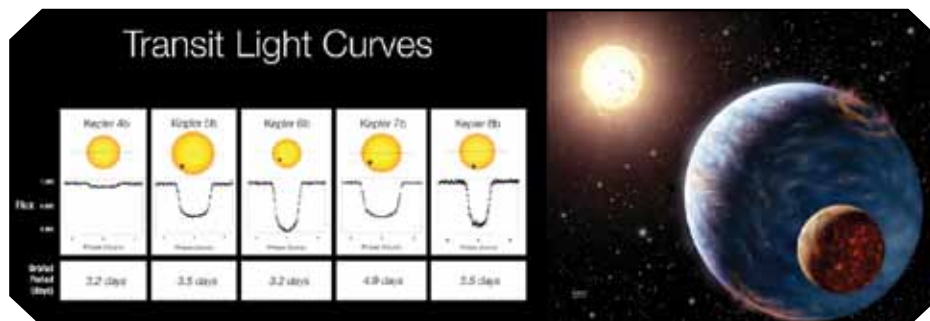


Figure 2-7. (Left) Planetary transits observed by the Kepler satellite [NASA/Kepler]. (Right) Artist's conception of an extra-solar planetary system. [NASA/Tim Pyle]

The first step in the quest for life in the Universe is the discovery of planets, and, in particular, Earth-like planets in the so-called “habitable zone” around other stars. Just twenty years ago, *no* planets were known outside the solar system. Using techniques developed by Canadians with the Canada-France-Hawaii Telescope (and prototyped with the NRC-HIA 1.2 metre telescope in Victoria), the first planet discoveries around normal stars were made in the 1990’s – albeit planets far from the ideals of supporting life as we know it. Now a total of more than 1000 planets have been discovered, many using techniques like those developed at CFHT.

In 2009, a Canadian team led by Christian Marois discovered 3 planets circling about the nearby star HR 8799 (see Figure 2-6) – a first using direct imaging and adaptive optics. The future is bright for such observations with the next generation of instrumentation: detection of terrestrial planets, and water in their atmosphere, is within reach of new instruments and telescopes in this decade. With a VLOT such as TMT, it may even be possible to detect the signature of microbial life (free oxygen) in the atmospheres of Earth-like planets orbiting nearby stars. Beyond this is the possibility of SETI-style

radio signal searches with large radio telescopes such as the SKA pathfinders, and with SKA itself in the next decade.

The search for signatures of life thus makes a major contribution to what is increasingly one of the most important questions, and explorations, in all of science – not just astronomy.

### 2.2 Canadian Astronomy Highlights of the Past Decade

The past decade has seen a number of advances and discoveries made by Canadian astronomers. These are described below.

Canadians have led the world in the direct detection of extrasolar planets. In September 2008, a Canadian team published the first image of a highly probable exoplanet orbiting another star. In November 2008, Canadians imaged a planetary system orbiting around the nearby star HR8799 (see Figure 2-6); images of this system made headlines all over the globe. This latter discovery is the fruit of novel high-contrast differential imaging techniques developed in Canada, techniques that are now widely in use on large 8-10m telescopes around the world.

MOST, a suitcase-sized microsatellite, was launched in 2003 (see §3.2), and continues to return data. MOST is Canada's first space telescope; its discoveries include new convective phenomena in the atmospheres of some stars, slow pulsations in hot stars, and planetary effects on the surfaces of stars.

BLAST, a balloon-borne sub-millimetre telescope, flew two missions. This telescope returned important results on the contribution of known sources to the cosmic infrared background, and on infrared sources in the Milky Way. BLAST was the subject of a major science documentary film that debuted during IYA and has been shown to millions in theatres, science museums and on TV.

Theorists at CITA participated in a series of groundbreaking experiments measuring the Cosmic Microwave Background; this has seen CITA evolve into a world-leading centre for analysis of CMB data sets.

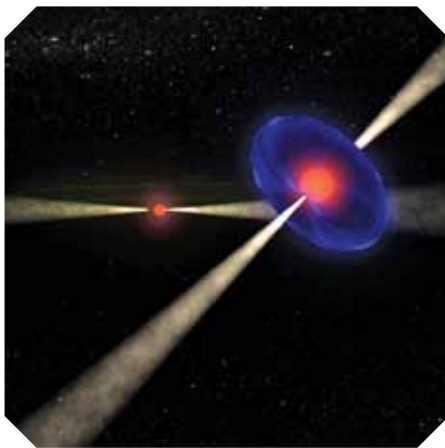


Figure 2-8. An artist's conception of the double pulsar, a "laboratory" for testing general relativity. [McGill University Office of Vice-Principal (Research and International Relations); McGill NCS Multimedia Services Animation by Daniel Cantin, DarwinDimensions]]



Figure 2-9. A pair of galaxies at a redshift of 0.3 (distance of about 3 billion light years) in the SNLS supernova survey. The left-hand panel shows a supernova near maximum light (about 10 billion solar luminosities) in the uppermost galaxy. The right hand panel shows the galaxies a few months later; the supernova has disappeared. [SNLS Collaboration/Julien Guy; based on observations from CFHT]

The middle of the decade marked the first time that researchers were able to simulate the evolution of individual galaxies in a galaxy survey-sized volume. Canadian researchers participated in this so-called "Millennium Run", which was the first simulation in cosmology to use over ten billion resolution elements.

The past decade saw the discovery of the amazing "double pulsar" (Figure 2-8) and its subsequent recognition as an unparalleled laboratory for testing General Relativity. Astronomers at UBC, CITA, and McGill modelled among other things the astonishing eclipses of one of the pulsars, measured the relativistic spin precession, and showed that it is consistent with that predicted in the strong-field regime by General Relativity.

Canadians discovered the most massive star known (116 times the mass of the sun). Scientists at U. de Montréal also discovered a new type of white dwarf with a pure carbon atmosphere.

The Gemini 8 metre telescopes (§3.1.2) went into full operation. Canadians

played a pivotal role in the design and construction of the adaptive optics system ALTAIR, and the multi-object imaging spectrograph, GMOS. Both of these facility instruments have been front and centre in Gemini's science.

The SCUBA sub-millimetre array on JCMT was completed in the late 1990's, and science results started to appear early in the decade. SCUBA revolutionized our understanding of star formation in the distant Universe, and of the evolution of galaxies.

Dark energy dominates the matter-energy density of the Universe, causing its expansion to accelerate with time (§2.1 and 5.1). Canadian scientists played a major role in the Supernova Legacy Survey (SNLS) using the Canada-France-Hawaii Telescope. This survey resulted in the discovery of nearly 400 distant supernovae at look back times up to 2/3 of the age of the Universe, and enabled the best determination of the nature of dark energy to date. Dark Energy appears to behave exactly like the "cosmological constant" first postulated by Einstein.

## 2.3 Canadian Astronomical Research in an International and National Context

### 2.3.1 International context

To place Canada's astronomy research program in an international context, an assessment of overall research productivity and quality is necessary. Given the large variation in economies and populations across the globe, comparisons are best performed by looking at relative statistics that take into

account these fluctuations, either by averaging or dividing by a normalizing factor. We can also assess the performance of individual observatories by a similar process. On a national basis we can consider the number of research awards, and prizes won.

Deriving statistics that measure research quality is non-trivial, and there are many possible choices. However, the LRPP strongly emphasizes that astronomy should be measured by the statistic it uses internally: paper citation statistics. Within international astronomy there is agreement

that the average number of citations per paper for a given country is a reasonable proxy for research quality. In fact, citation statistics directly measure the *relevance* of research.

The assessment of a given country's contributions proceeds by adding citations associated with any paper that has at least one author from that country. From a multi-year average citation rate, the relative citation impact factor (CIF) can then be assessed by dividing Canada's value by the world average.

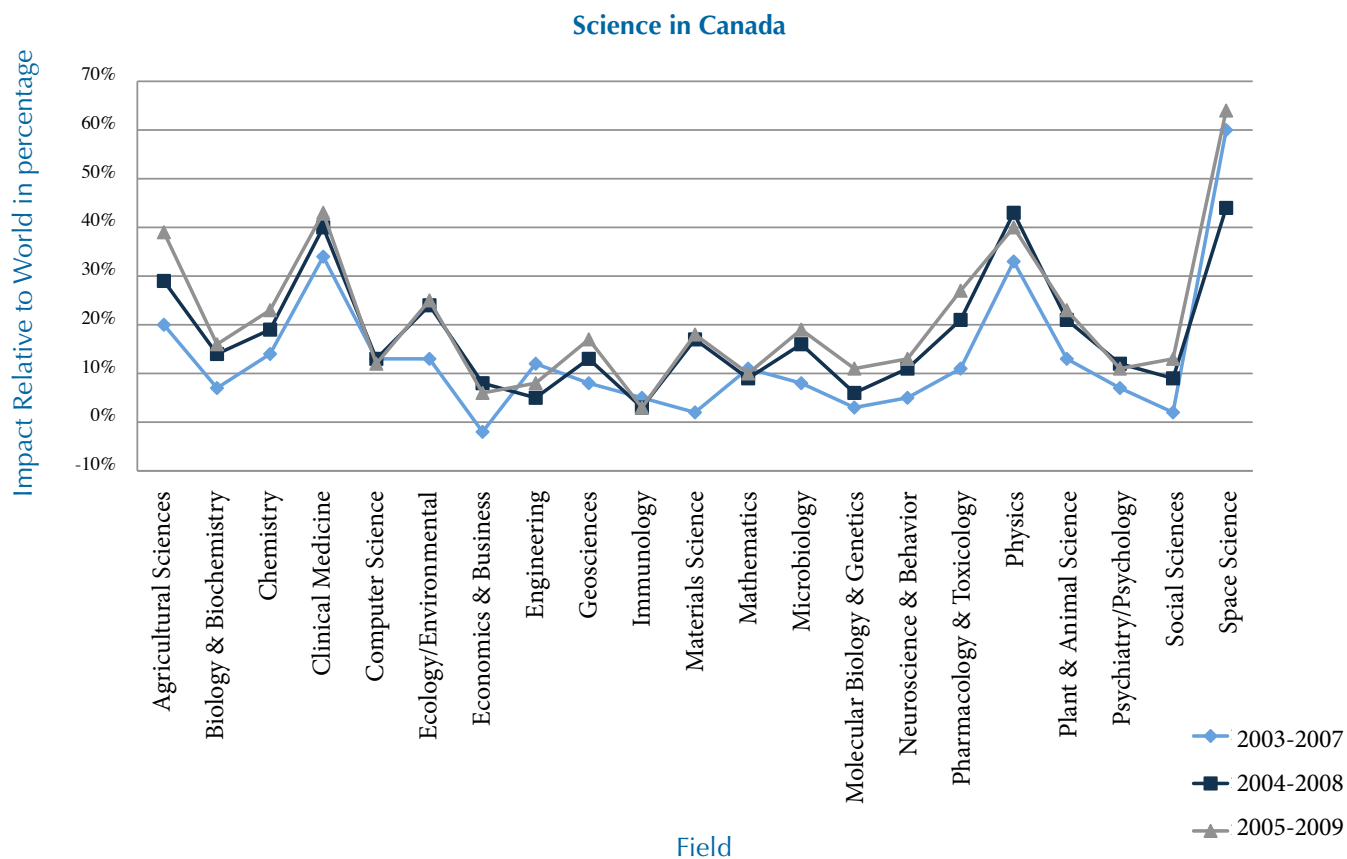
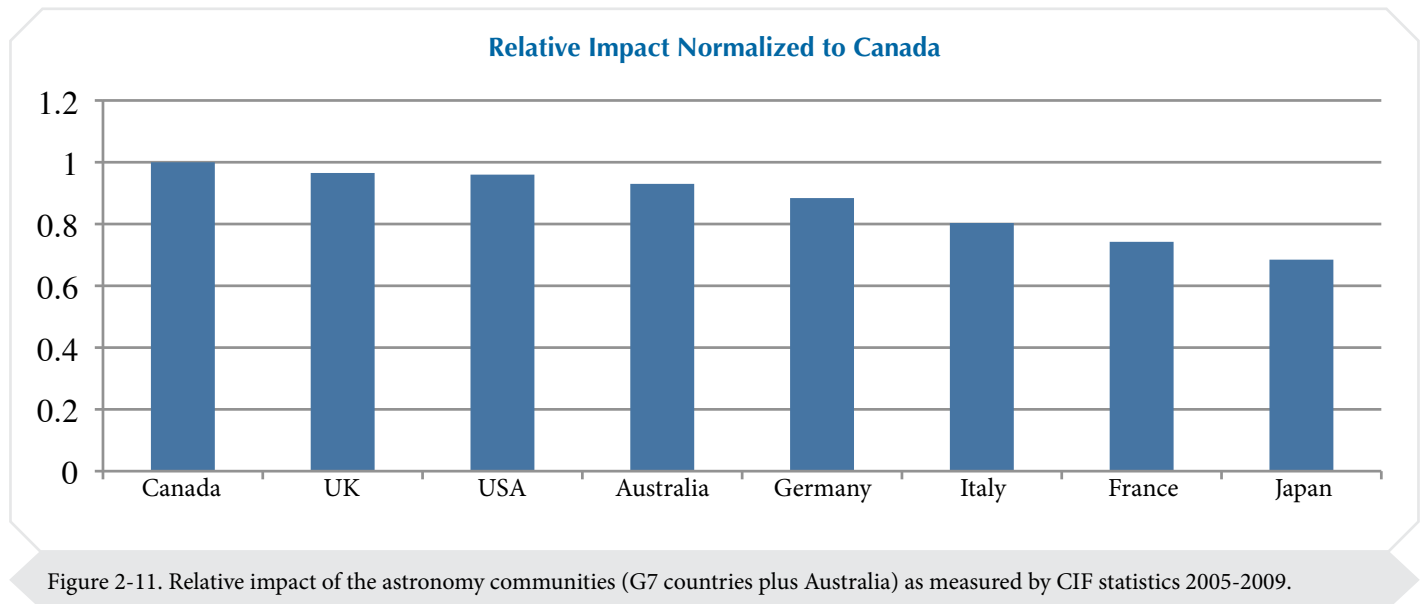


Figure 2-10 Relative impact of Canadian science as a percentage above the world average citation rate, for different date ranges.





In Figure 2-10 we plot 22 Canadian science areas according their CIF rating from the Thomson Reuters (ISI) data<sup>5</sup>. The highest ranking field is Space Science, which includes astronomy, at an exceptional 64% above the world average. The second and third place subject areas are Clinical Medicine (43%) and Physics (40%).

In Figure 2-11 the relative impact of countries as measured by average citations per paper is shown (again from Thomson Reuters (ISI) data 2005-2009). We have restricted the countries plotted to include the G7 plus Australia, and have normalized by Canada's value to unity. Canada ranks highest of all these countries and is fourth in the world behind the (much smaller) countries Hungary, Scotland and Israel. In the period 1995-2005 Canada was ranked first in the world across all nations.

Canada's number one ranking is also confirmed by a June 2010 study by The Times Higher Education magazine in the UK<sup>6</sup>.

The Council of Canadian Academies (CCA) also reported in 2006 on the impact of publications in different science and technology fields. Based upon their statistical analysis of astronomy, astrophysics and cosmology, the CCA commented in their report:

*"Canada has exceptional strength in Astronomy, Astrophysics and Cosmology... that has increased over time in a self-reinforcing way – excellence begets further excellence."*

This success can also be measured in terms of the impact of the observatories in which Canada participates. Restricting to optical, infra-red and sub-millimetre, Canada has shares in CFHT, Gemini and the JCMT. In these statistics each observatory is given credit in papers where combined data is used. In Figure 2-12 we plot the average impact per paper (from citations) in the years 2005-2009. CFHT has clearly been exceptionally successful, and produced the highest impact per paper in 2007. This success can be directly attributed to the groundbreaking Legacy Survey program made possible by MegaCam. Equally interesting is the average impact of the Gemini telescope. Despite difficulties with funding and delays in commission instruments it has consistently performed as well as, and in most years better than, the VLT and Subaru. However, in the 10m telescope class, the dominant observatory remains Keck.

<sup>5</sup> [http://sciencewatch.com/dr/sci/10/may2-10\\_2/](http://sciencewatch.com/dr/sci/10/may2-10_2/)

<sup>6</sup> <http://www.insidehighered.com/news/2010/06/10/citations>

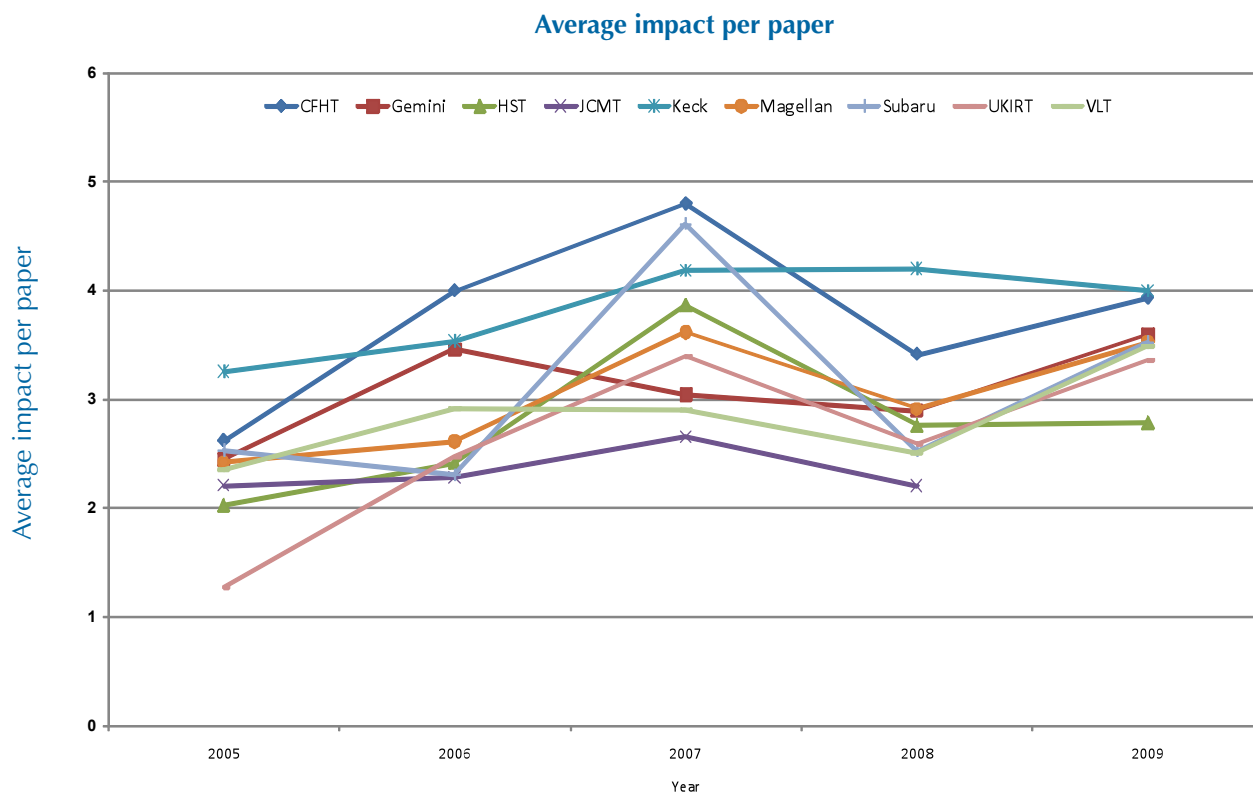


Figure 2-12. Average impact per paper for different optical and infrared astronomical facilities [courtesy D. Crabtree].

### 2.3.2 National Context

In terms of accomplishments nationally, in the period 2000-2010, Canadian astronomers received 1 Herzberg medal, 1 NSERC Polanyi Prize, 4 E.W.R. Steacie Memorial Fellowships, 4 Discovery Accelerator Awards and 24 Canada Research Chairs.

The 24 CRC chairs in astronomy, for a faculty complement of about 200 across Canada, yields one CRC per 8.3 faculty. Across the entire science and engineering faculty complement in Canada, there is 1 CRC per 13.7 faculty. One may conclude that Canadian astronomy has been very successful in securing CRC chairs. While the 24 CRCs represent 1.0% of the overall CRC allocation, the

proportion of professors in Canada employed in astronomy is 0.5% (200 of 39,855, CAUT statistics) of the total number of academic appointments in Canada, indicating an above average apportioning of CRCs to astronomy.

The 4 Steacie Fellowships compare to 11 in Chemistry in the same time period (approximately a factor of three higher), while the ratio of the two professional populations, is  $921/200=4.6$  (CAUT statistics). Biosciences received 20 Steacie Fellowships (5 times as many as astronomy), while the ratio of the two professional populations is  $1731/200=8.6$  (CAUT statistics). Clearly, astronomy is significantly above average in prize fellowship awards, though one must beware of small number effects.

Summarizing §2.3.1 and §2.3.2, the broad spectrum of success of Canadian astronomy has all been achieved despite comparatively low investment as compared to the international average (see §6.2). Aside from raw talent, innovative science and a work ethic second-to-none, the success of Canadian astronomy can be closely linked to a careful choice of projects and facilities. Effective national organization and communication within the profession have made this possible. By ensuring access to a suite of world-class facilities that provides broad multi-wavelength coverage, we have been able to build a number of strong university programs. Future success will depend on being able to maintain access to state-of-the-art facilities supported by a network of capable HQP.







Image: Canada-France-Hawaii Telescope/Coelum



## 3. Existing Facilities and Institutes

### 3.1 Ground-based Facilities

This section reviews a variety of existing or “soon-to-exist” facilities. It includes ALMA (early science operational start late 2011), and JWST (scheduled launch date 2015), both of which are fully-funded and nearly completed. It also includes a discussion of a variety of institutes and laboratories that are pivotal to the success of the Canadian community.

#### 3.1.1 CFHT

The Canada-France-Hawaii Telescope (CFHT) is a 3.6 metre aperture telescope

located on the best-seeing site of the 4200 metre summit of Mauna Kea, Hawaii. The telescope was constructed in the 1970's, and went into operation in 1979. It is owned and operated by Canada (42.5%), France (42.5%), and Hawaii (15%).

Canada's entry into the CFHT project in the early 1970's signalled a major shift in Canadian astronomy. CFHT represents Canada's first venture into international astronomy, and one of the first major overseas endeavours in all of Canadian science. More importantly, CFHT was our first internationally competitive facility: it quickly became the leading 4 metre-class telescope in the world. CFHT gave us superb experience in areas of astronomy

previously un(der)developed in Canada and in the world – specifically high resolution imaging at the best location on one of the finest astronomical observing sites in the world. Finally, the experience of developing state-of-the-art instrumentation for CFHT has paid off in placing Canadians in a leading position for developing instruments for much larger telescopes such as Gemini and, in the future, a VLOT such as TMT.

CFHT has established an outstanding reputation in international astronomy. Citations from its publications continue to rank very high (\$2.3). An aggressive and cutting-edge instrumentation program at this telescope has set it



Figure 3-1. The Canada-France-Hawaii Telescope – exterior view at sunset. [J.-C. Cuillandre (CFHT)]

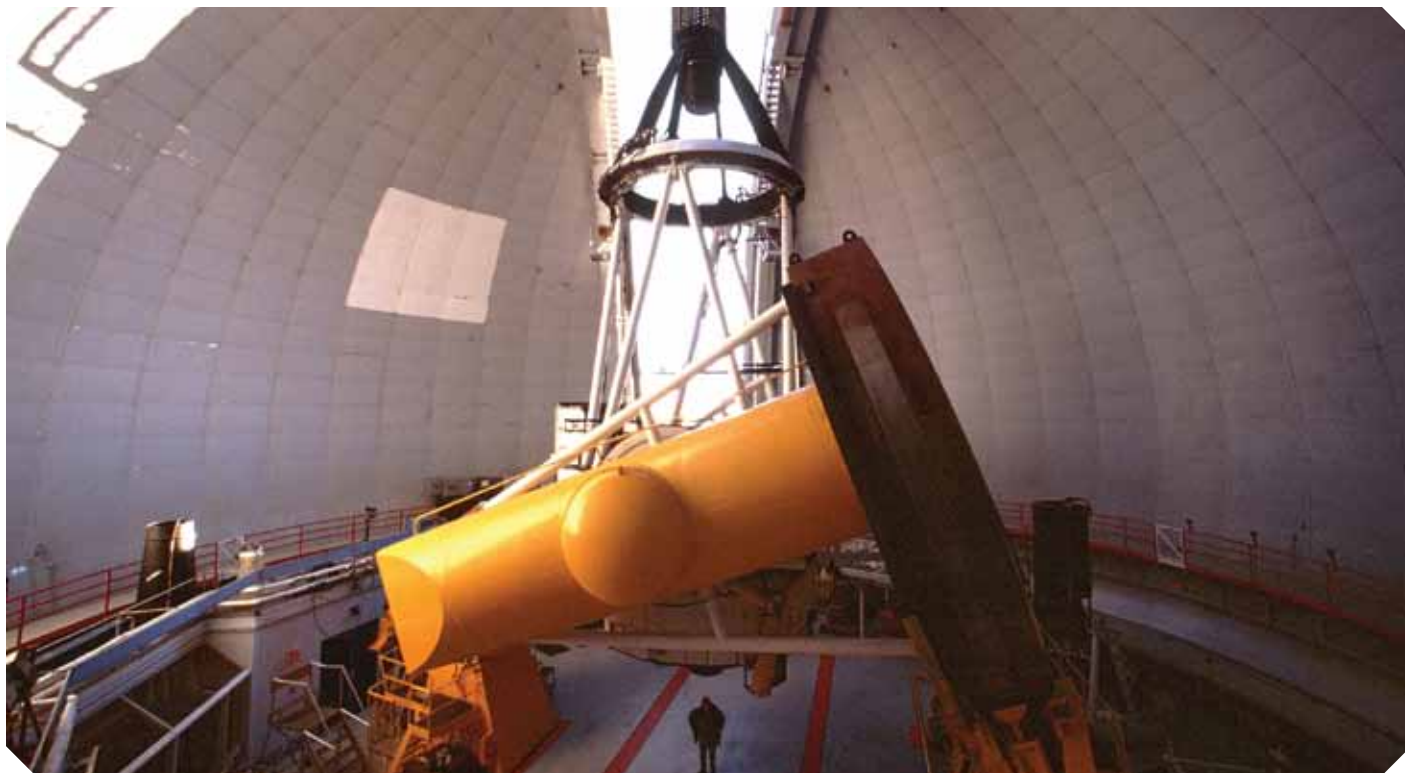


Figure 3-2. The CFHT and dome. [J.-C. Cuillandre (CFHT)]

apart on the international stage. Since 2002 CFHT has owned one of the largest imaging cameras in the world. This telescope has also led the world in the development of astronomer-friendly adaptive optics systems – success in which has led to our building the Gemini adaptive optics system ALTAIR, becoming a major player in the Gemini Planet Imager, and now has allowed us to be the prime contractor for the TMT NFIRAOS AO system.

CFHT has been responsible for many major discoveries over the past few decades. CFHT (and Canada) led the way in the development of techniques for the discovery of extra-solar planets (Campbell, Walker and Yang 1989). More recently CFHT and its magnificent MegaCam camera have led to the best characterization to date of the nature

of Dark Energy in the Universe.

Instrumentation development continues apace at CFHT. An aggressive new instrument program, coupled with changes to the telescope and dome, would, if funded, transform the facility over the next few years. Three instruments are being considered; it is likely that only two will be built.

- The 'Imaka instrument will provide high quality (0.3 arcsec) images over a square degree of sky, complementing other imaging telescopes to be built this decade, such as LSST (larger field but lower resolution). The feasibility of 'Imaka is still being assessed at the time of writing.
- The SPIROU near-infrared high resolution spectrograph will be capable of detecting Earth-like planets in the

habitable zone of low-mass stars, and will also investigate the role of magnetic fields in the star/planet formation process.

- GYES is a wide-field medium resolution multi-object spectrograph that will provide followup stellar spectroscopy for the Gaia satellite project led by ESA. The project is being led by France.

In addition SITELLE (a visible imaging Fourier Transform Spectrometer) is a new CFHT guest instrument already funded by CFI, and which is due for operation in 2012. SITELLE will be used to study the dynamics and abundance trends of galaxies and the physics of the interstellar medium. SITELLE will open a new unexplored discovery space: integral field spectroscopy in visible light over a wide field.



Figure 3-3. The Gemini Observatory North Telescope on Mauna Kea. [Gemini Observatory/Association of Universities for Research in Astronomy]

CFHT is a wide-field, high resolution 4m-class telescope. As such it is complementary with the narrow-field science capabilities of Gemini, and, in the future, with TMT. The site is “prime real estate” on Mauna Kea, and can accommodate a telescope of aperture up to 15 metres. Whether the redevelopment of the CFHT site is feasible depends on many factors, both technical and strategic. This is discussed further in §4.2.4.

### **Recommendation 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.*

### **3.1.2 Gemini**

The Gemini Observatory consists of twin 8 metre telescopes, one in Chile (Cerro Pachon, altitude 2700m), and one in Hawaii (Mauna Kea, 4200m). The Gemini partnership currently (2010) comprises the US (50.1%), the UK (23.8%), Canada (15.0%), and smaller shares for Australia (6.2%), Argentina (2.4%), and Brazil (2.5%). At the end of 2012, the UK will withdraw from Gemini and its share will be distributed among the remaining Parties, as agreed to by the Gemini Board.

Gemini is currently Canada’s forefront ground-based optical-infrared astronomical facility. A panel of Canadian astronomers (the Gemini Assessment Point Panel) recently evaluated the desirability of continuing Canada’s participation in the Gemini Observatory. The panel’s report in November 2009 was strongly positive; to quote the GAP report:

*“... relative to the broader international community, Canadian-led Gemini programs have produced greater-than-average publication and citation rates, both strong indicators that the research community is using the facilities imaginatively, to strategic advantage, and with consequently far-reaching scientific impact. Moreover, Canadians have been conspicuously interactive in striking international collaborations based upon Gemini research, and it is clear that the Canadian astronomical community’s scientific presence and influence have been materially advanced through our participation in the Gemini Observatory.”*



In spite of this strong endorsement, there exist concerns for the future.

(i) The “Aspen” instrumentation program was abandoned, and consequently urgently-needed new instruments have been shelved. (ii) With the departure of the UK, Gemini will operate post-2012 on 75-80% of its current operating budget (unless additional funds are found). How this will affect the science output of the telescopes remains to be seen. (iii) Astro2010 has proposed a significant alteration of the observatory’s governance structure by unifying Gemini with NOAO. If implemented, this re-organization, coupled with the increased share of the observatory that the US will have post-2012, could significantly diminish Canada’s voice in management and scientific decision-making.

In the longer term Canada will need to find operating funds for a VLOT, and further in the future, for SKA. A strong case can be made for finding these funds by withdrawing from Gemini as a VLOT becomes available. Gemini’s design emphasizes very high adaptive-optics-assisted image quality within a fairly narrow field-of-view. These design goals are shared by both TMT and E-ELT; when the next generation of 30m-class telescopes comes online the central capability of the Gemini telescopes

will be surpassed. This situation is quite unlike that faced by CFHT when Gemini came on-line: CFHT’s main strengths (good natural image quality over a very wide field of view) remain quite complementary to those of Gemini, even though the telescope itself is smaller.

Furthermore, Canada’s large share of CFHT, coupled with the cohesiveness of the Canadian national astronomy program, has directly enabled large signature projects in which Canadian investigators have played a leading role (e.g. the CFHT Legacy Surveys).

Given the limitation in the field of view of the Gemini telescopes, and Canada’s limited voice in the Gemini partnership, it is hard to see how continued participation in Gemini will remain of primary importance to Canada when a VLOT comes online. Therefore the LRPP makes the following recommendation:

### **Recommendation 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.*

### **3.1.3 ALMA**

Ranked as the top priority in LRP2000, the Atacama Large Millimetre/Submillimetre Array (ALMA) is the first of the great “World Observatories”. It is situated at an altitude of 5000m on the Chajnantor plain of the Chilean high desert, one of the best sites on the planet for sub-mm observing. At a total project cost of approximately \$1.3B (US), the observatory brings together new leading-edge antenna and receiver technology that will allow detection of molecular radiation 10-100 times fainter than current limits. In addition to this increase in sensitivity, ALMA will also provide exceptional resolution on the sky. Despite observing at a vastly longer wavelength than next generation giant optical telescopes like the TMT, the spatial resolution will be similar – resolving a hair’s width at a distance of over 2 km. These advances in resolution and sensitivity have been made possible by ALMA using a reconfigurable array of 66 dish antennas that work together in different configurations. ALMA is poised to open up entirely new fields of study, from planet formation to cosmology.



Figure 3-4. (Left) Eight antennas at the ALMA site. [ALMA (ESO/NAOJ/NRAO)] (Right) Artist’s impression of the appearance of the full ALMA array on the Chajnantor Plain. [ALMA (ESO/NAOJ/NRAO)]





Figure 3-5. (Left) ALMA Band 3 receiver cartridges designed and built at the NRC Herzberg Institute of Astrophysics. [NRC-HIA] (Right) One of the 130 ton transporters carrying a 115 ton antenna. [ALMA (ESO/NAOJ/NRAO)]

Since the MTR2005 a number of important events have occurred. First, Japan joined the collaboration in late 2004, providing funding for three additional receiver bands and the 16 antenna Atacama Compact Array. Second, in 2007 the telescope underwent a de-scoping exercise as construction costs became more fully appreciated. However, through a judicious series of choices, including reducing the number of antennas in the main array (excluding the Compact Array added by Japan) from 64 to 50, the project has coped without significantly impacting the overall science case. The Array Operations Site was completed in 2008 and by 2011, 16 antennas will have been delivered and this will be the configuration used in the early science phase. Full completion (50 antennas) is now scheduled for 2013, with early science in late 2011.

#### *Canada's Contribution to ALMA*

Entry by Canada into the ALMA project was one of the primary motivations behind the North American Program

in Radio Astronomy (NAPRA) agreement with the US. NAPRA is perhaps the single most significant success of LRP2000, having overseen the successful participation of Canada in the ALMA project and the building of the WIDAR correlator for the Expanded Very Large Array (EVLA).

Canada's role in the design, construction and future operation of ALMA has been significant. The millimetre instrumentation laboratory at the HIA is overseeing the production of 73 "Band 3" (84 -116 GHz) receiver cartridges for the telescope. These are the first and most important complement of receivers for ALMA. The design and construction of these receivers was made possible by HIA's expertise in the application of superconductor technology to millimetre wave detection. Canadian companies have also been significant beneficiaries, receiving contracts to produce components for these receivers, and also the ALMA Master Laser, a critical timing reference system permitting the accurate combination of the antenna signals (see Appendix F for details).

The NRC's Canadian Astronomy Data Centre (CADC) is contributing expertise to the planning of the ALMA Data Archive Centre in Chile, where immense amounts of data will be stored for users of ALMA. Making such large volumes of data rapidly accessible over comparatively slow networks is a significant technical challenge. The University of Calgary and McMaster University contributed to the ALMA offline software and pipeline development. This pipeline will be used by every astronomer analyzing ALMA data, and will have stringent quality and ease-of-use requirements. These requirements will set the standard for the EVLA, for the SKA pathfinder instruments MeerKAT and ASKAP which are presently under construction, as well as for SKA.

Overall, Canada is extremely well-placed to take advantage of this exceptional facility, both during the early science phase, and in full operations.

### Outstanding issues

Canada's contributions to the ALMA project have been immensely successful; yet there are still outstanding issues to be addressed. Most critical of these is Canada's contribution to the overall operations cost, namely the 2.72% of the total operational budget. In agreement with previous LRP recommendations, if no new funding for JCMT operations can be found, then a staged withdrawal from the JCMT to fund ALMA operations will be necessary (see §3.1.4). Now that ALMA is nearing completion, attention is turning to development projects that will further augment the facility around the 2020 time-frame. For example, while ten specific frequency ranges were identified in the initial design, two receiver bands were omitted from the telescope's initial configuration for budgetary reasons. One of these – “Band 1” (31-45 GHz) is of special interest to Canada because it will allow measurement of the Sunyaev-Zel'dovich effect on the Cosmic Microwave background, a field in which Canada has world-renowned

expertise, including a Herzberg Medal winner. However, a number of alternative technical development projects are possible, and Canada needs to be prepared to respond to new opportunities for HIA, the universities and Canadian industry. Selection of specific technology development areas is likely to be a competitive process, where groups will submit proposals for projects that are identified as a high priority.

### Recommendation 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.*

### 3.1.4 JCMT

The James Clerk Maxwell Telescope (JCMT) is arguably the most powerful ground-based sub-mm observatory in the world, and will remain so until ALMA becomes operational early in this decade. With a share of 25%, Canada is an important partner in this observatory, together with UK (55%) and The Netherlands (20%). JCMT has been among the most scientifically productive astronomical observatories; citations in the early years of the past decade were very high, largely due to SCUBA, an instrument designed to image cosmic dust at sub-mm wavelengths. SCUBA enabled the discovery of a new class of object (dust-obscured primordial galaxies) known ever since as “SCUBA galaxies”, and on the basis of this and other discoveries (local star formation, for example), sub-mm astronomy has exploded in recent years (ALMA, Herschel, CCAT). The legacy of SCUBA has driven the entire strategy for the continued development of the field.

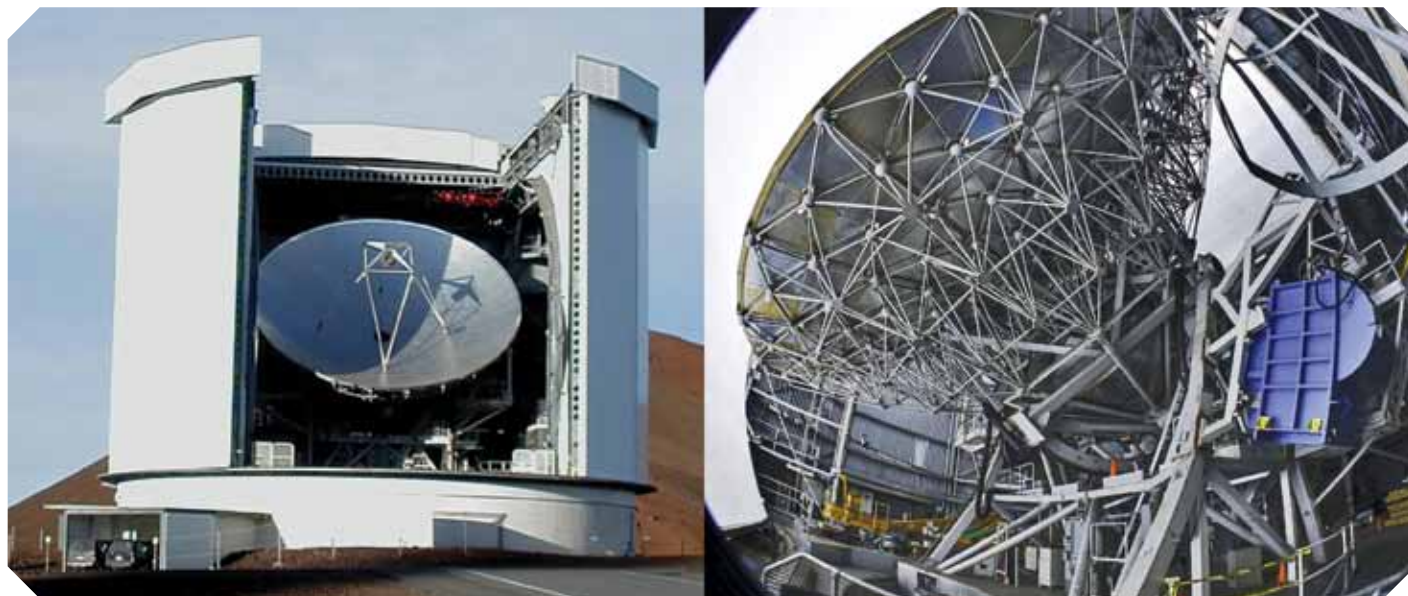


Figure 3-6. (Left) The James Clerk Maxwell Telescope, Mauna Kea, Hawaii. [Joint Astronomy Centre] (Right) SCUBA-2 fully assembled on the rear of JCMT. [Antonio Chrysostomou/Joint Astronomy Centre]





Figure 3-7. The Very Large Array, Socorro, New Mexico. [NRAO]

SCUBA ended its operation in 2005 and its success led to the development of SCUBA-2, an instrument that is expected to be up to one thousand times more powerful than its predecessor. Canada was and is an active player in the development of this new instrument through a major grant from CFI, which also funded two auxiliary instruments to be used with SCUBA-2 – a polarimeter (POL-2) and a Fourier Transform Spectrometer (FTS-2). Originally scheduled for operation in 2006, early science data were obtained in 2010. SCUBA-2 has been the cornerstone of proposed ambitious Legacy-class surveys, developed and led by Canadians, to study the submillimetre Universe to an unprecedented level of sensitivity. The main challenge facing JCMT is how to take advantage of SCUBA-2, given the small period available (less than 1 year) before the telescope's current partnership ends on March 31, 2012. In addition, the performance of SCUBA-2 appears to be lower than expected, making these Legacy surveys a challenge to complete in their present form. Some SCUBA-2 science is now being tackled with the recently

launched far-infrared/submillimetre Herschel Space Observatory (though not at the longer wavelengths that SCUBA-2 can observe).

#### **Recommendation 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 (potentially descope) SCUBA-2 surveys.*

#### **3.1.5 EVLA**

The Expanded Very Large Array (EVLA) is a major upgrade of the Very Large Array (VLA), the flagship centimetre radio telescope of the National Radio Astronomy Observatory (NRAO). The \$90M upgrade began in 2001 and will be complete in 2012. The EVLA represents an improvement in observational capability by several orders of magnitude compared to that of the VLA. Operating over a contiguous frequency range of 50 GHz, the EVLA will have an instantaneous bandwidth 80 times that of the VLA providing a sensitivity improvement of a factor between 10 and 10,000, depending on the type of observation. As such it will be the most powerful radio telescope in the world, and will revolutionize the field of radio astronomy.

The sensitivity, frequency bandwidth and unprecedented spectral capability of the EVLA will allow astronomers to transform several key areas of astrophysics. For example, its polarization capability will allow observers to trace the magnetic fields in X-ray emitting

galaxy clusters and in thousands of spiral galaxies. The EVLA will permit imaging of the chemical and physical structure of the densest and most obscured regions of nearby starburst galaxies, galactic star forming regions and planetary atmospheres, as well the measurement of the star formation rates in the most distant and youngest galaxies in the Universe. Its sensitivity will allow observations of many tens of Gamma Ray Bursters every year, perhaps permitting at last a definitive determination of the size, structure and evolution of these enigmatic objects.

The EVLA is relevant to Canadian astronomy in 2010-2020 in two important ways:

First, under the North American Program in Radio Astronomy (NAPRA) established during the last plan period, Canada provided the new correlator for the EVLA, which combines the signals

from all 28 antennas permitting the formation of the radio source image. NAPRA is the route by which Canada entered ALMA, and guarantees Canada access to the EVLA and all other radio telescopes operated by NRAO. The EVLA correlator was designed and built by DRAO of the NRC-HIA at a cost to Canada of about \$20M, and involves a novel design called WIDAR. It is this correlator that plays a principal and essential role in the transformative capability of the EVLA. Figure 3-8 shows the correlator in the final stages of its assembly prior to delivery to the telescope.

Second, the EVLA operates at a similar wavelength range to the SKA, and though the EVLA has a smaller collecting aperture than the SKA by about a factor of 50, it will be an important pathfinder for SKA science. Since the analysis software will be highly automated, it will also be

a pathfinder for data analysis. The EVLA will be the first major radio observatory to offer easy use by the broad astronomy community, including those not necessarily trained in the specialized techniques of radio interferometry.

Canada will be a key partner in the SKA project, and thus the EVLA will serve to engage Canadian astronomers at an early stage in SKA science. The LRPP thus makes the following recommendation:

### **Recommendation 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.*



Figure 3-8. The WIDAR correlator racks being assembled at HIA-DRAO in Penticton, BC prior to shipment to the EVLA in New Mexico. [NRC-HIA]



## 3.2 Space Facilities

The last decade has seen remarkable achievements in Canadian Space Astronomy. Canada has taken the ambitious step of joining the James Webb Space Telescope (JWST) project as an international partner, in accordance with the recommendations of LRP2000. JWST is the single largest investment in Canadian astronomy. In addition, Canada has made significant contributions to a number of productive international satellite missions (e.g. Herschel and Planck), played a pivotal role in several high-profile stratospheric balloon experiments, and taken the lead in its own microsatellite mission.

More specifically, in the last decade, we have been directly involved (through the Canadian Space Agency, CSA) in the following seven Space Astronomy missions.

- VSOP (1997-2005): Space-based radio interferometry mission, led by Japan. CSA provided funds for Canadian participation.
- ODIN (2001-2006): Sub-mm orbital observatory, led by Sweden. CSA provided funds for the OSIRIS instrument, used for infrared spectroscopy.
- FUSE (1999-2007): Far-UV satellite, led by the US. Canada provided two fine guidance sensors that allowed the observatory to be aimed at its targets with very high precision. CSA provided funds for Canadian participation, including two astronomers based at the operations centre. FUSE was an outstanding success for Canada, with numerous Canadian publications; in many ways it led to Canada's participation in JWST.
- BLAST (2003-2006): Balloon-based experiment to study star formation, led by the US. Canada provided the gondola, pointing control system, data acquisition system, flight and

ground station software, power system, and overall system integration, funded primarily by CSA.

- MOST (2003-): The MOST (Micro-variability and Oscillation of STars) micro-satellite was designed to study stellar pulsations, and has also made notable discoveries in exoplanetary science, including the recent discovery of a star tidally locked by a giant exoplanet. In many ways MOST has been the pioneering precursor of ambitious space missions led by other nations (the French CoRoT satellite and NASA's Kepler mission). MOST was designed and built in Canada, and was the first astronomical microsatellite. CSA contributed \$15.6M to MOST. The successors to MOST are NEOSat and BRITE (\$5).
- Herschel (2009-): Far-infrared and sub-mm telescope, probing some of the coldest and most distant objects in the Universe; led by the European Space Agency. Canada contributed to the SPIRE and HIFI instruments. Discussed in more detail in §3.2.2.
- Planck (2009-): Cosmic microwave background telescope, designed to create all-sky maps of the anisotropies of the Cosmic Microwave Background radiation with uniquely high angular resolution and sensitivity. Canada provided data analysis tools and other software; funded by CSA, led by ESA.

In addition to these completed or currently operating missions, Canada is involved in several missions that are scheduled to fly in the near term, all CSA-funded:

- EBEX (2009-2011): Balloon-borne polarimeter designed to measure the intensity and polarization of the cosmic microwave background radiation. The EBEX CMB polarimeter was test flown in June 2009, achieving the first demonstration in a space-like

environment of a large array of Transition Edge Sensor bolometers and of a SQUID-based multiplexed readout system.

- Astrosat (2010-): UV-X-ray satellite, led by the Indian Space Agency. Canada designed the readout electronics for the UV instrument, UVIT, and was in charge of integrating, testing, and calibrating the detector for this instrument.
- JWST (2015-): Successor to the Hubble Space Telescope. Canada is providing the Fine Guidance Sensor (guider) and the Tunable Filter Imager (science instrument). Discussed in detail below.
- NEOSat and BRITE: two micro-satellites discussed further in §5.4.

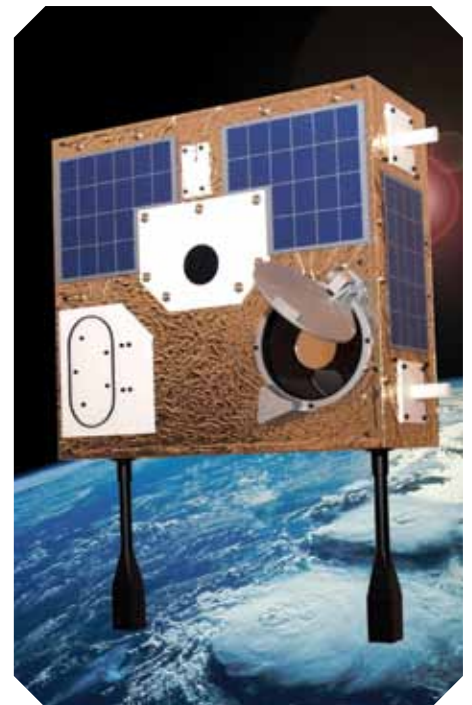


Figure 3-9 Canada's MOST satellite performs ultra-high-precision photometry (i.e., measurement of brightness variations to a level of 1 part per million) of stars down to the naked-eye limit of visibility. MOST is Canada's first space telescope. [Canadian Space Agency]

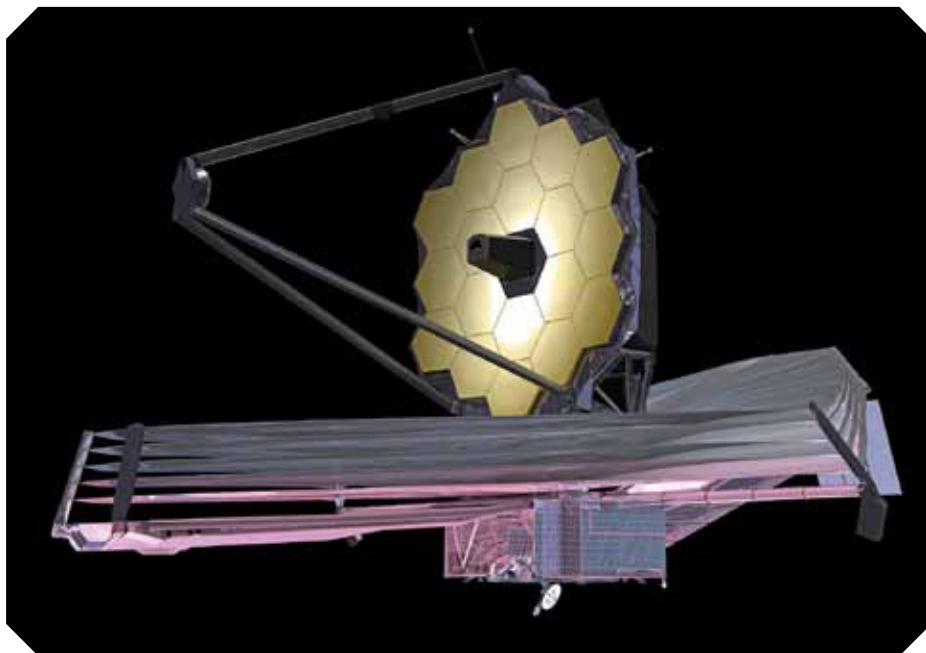


Figure 3-10. The James Webb Space Telescope (artist's impression). [NASA/JWST]

In what follows, we discuss two missions that Canada has been heavily involved with: Herschel (launched 2009), and the James Webb Space Telescope (JWST – to be launched around 2015). The reader is referred to §5 for future missions that have not yet been funded, and §6.4.3 for a general discussion of the Canadian Space Agency and its role in Canadian astronomy.

### 3.2.1 JWST

The James Webb Space Telescope (JWST) is the successor to the Hubble Space Telescope (HST). The Canadian Space Agency is one of the three partner agencies in the JWST mission (together with NASA and the European Space Agency). The telescope will open new frontiers in astronomy, ensure Canada's position as a leader in Space Science, and advance technology in several key areas. The JWST is a critical foundation for future developments in Canadian astrophysics.

The long-term plans for astronomy in Canada (this document), in the United States (Astro2010 Decadal Survey), and in Europe (Astronet's "Science Vision for European Astronomy") are based on the assumption that JWST will be operating in the coming decade.

Canada will invest about \$150M CDN in the JWST project, which is approximately 2.5% of the total cost of the mission. It should be noted that Canada will be allocated no less than 5% of JWST's observing time for this 2.5% investment. In addition, Canadian astronomers will be granted guaranteed observing time as a result of Canada's development of the FGS/TFI instrument (see below).

JWST is expected to launch in 2015 and to begin science operations in 2016. The telescope will operate at cryogenic temperatures (40 degrees above absolute zero) with a mirror that is nearly 7 times larger in area than that of HST (6.5m vs. 2.4m in diameter), allowing the telescope

to see much deeper into space. By some measures, JWST will be about 100 times as powerful as the HST. Unlike HST, which operates mainly in the visible and ultraviolet wavebands, JWST is optimized for operation in the near-infrared and mid-infrared, and will be positioned at the L2 Lagrangian point, about 1.5 million kilometres from the Earth, rather than in low Earth orbit, as is the case with HST. A disadvantage of operating at L2 is that the telescope will not be serviceable by astronauts, so the mission's 5-year to 10-year lifetime is an important operational constraint. (The Hubble Space Telescope has now been operating for 20 years, and has been serviced and upgraded by astronauts four times.)

The sensitivity of JWST will be limited by the natural zodiacal background (i.e. emission from faintly glowing dust particles in the solar system). For imaging observations in the infrared, the sensitivity of JWST will exceed that of ground-based observatories by factors of 10 to 100,000. JWST's infrared imaging capability is wonderfully synergistic with upcoming next-generation ground-based facilities: many new classes of objects will be discovered by JWST, and these will then be followed-up by 30m-class ground-based telescopes for detailed spectroscopic inspection.

The science themes upon which JWST's design is based have been broadly divided by the project office into four areas: "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". In summary, the James Webb Space Telescope has been designed to undertake an extraordinarily ambitious science program that explores the Universe at scales from the very small (the solar system) to the very large (superclusters of galaxies),

and from cosmic times that span the full range from the present epoch all the way to the dawn of the first luminous sources that formed in the Universe.

JWST consists of a telescope and four science instruments. These instruments are: NIRCarn, a Visible/Near Infrared Camera; NIRSpec, a Near-Infrared Multi-Object Dispersive Spectrograph; MIRI, a Mid-Infrared Camera-Spectrograph; and FGS/TFI, a Fine Guidance Sensor and Tunable Filter Imager. The latter instrument was designed and manufactured in Canada, and represents the nation's main contribution to the JWST project. The main component of this instrument, FGS, will provide continuous pointing information to the observatory, which will be used to stabilize the line of sight, allowing JWST to obtain its required image quality. The FGS is so critical to the operation of the observatory that it is designed with two independent channels, each of which is completely redundant in terms of the guiding function; the FGS pointing accuracy is equivalent to the width of a hair at a distance of 4 km. The Tunable Filter Imager component of the instrument is packaged within the FGS, but is intended to be used solely for science observations. The instrument is designed to image a relatively large area of the sky at a single wavelength, and is optimized for the detection of the first galaxies, and for the detection/characterization of exoplanets.

At present the telescope has met its technological development goals. Delivery of the 18 mirror segments is on schedule for 2011, with four segments plus the secondary and tertiary mirrors already polished and within specifications. A recent cost review exercise (the Independent Comprehensive Review Panel led by John Casani) has identified a number of factors leading to the project being over-budget and recommended a number of changes to the project's

management structure, and cautioned that the launch may be delayed. However, it is important to note that the HST's technical development and schedule met similar challenges. In FY 2011 dollars the HST's cost (\$5.8 billion) is nearly identical to that of JWST even though the JWST is much larger and more powerful. No one would doubt that the Hubble Space Telescope was worth this effort and cost, given the manner in which it revolutionized human perception of the Universe, and inspired a whole new generation.

### *Issues and Recommendations*

*Project Schedule* – The James Webb Space Telescope project has recently completed a successful Critical Design Review, but, as noted above, the ambitious scale of the project makes a delay in the launch date a real possibility.

### *Recommendation 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.*

*Operational Model* – The JWST operations plan is based on that used for existing space observatories. The majority of JWST observing time will be allocated to the international astronomical community through annual peer-reviewed proposal opportunities. This operational model presents challenges to Canadian astronomers, because time awarded on the telescope will not necessarily be synchronized with funding opportunities for using the data. This is unlike the situation in the United States, where time awarded on spacecraft is accompanied by financial support to the PI's in order to maximize the impact of their own observations through speedy analysis before the data are released publicly. Because space science data analysis is under-funded in Canada (see §6.4.3), the astronomy community may not be reaping the full benefit of Canada's investment in missions. The LRP2010 panel's recommended solution to this problem is to associate funding with successful proposals that use CSA-funded missions. This recommendation appears in Sections 6.4.3 and 7.3.

### **3.2.2 Herschel**

The 3.5 metre Herschel Space Telescope is the largest space telescope ever launched. It targets the 60-600  $\mu\text{m}$  wavelength range, bridging a gap between earlier infrared space missions and ground-based facilities. Its science goals span a vast range of cosmic epochs and cover a wide range of subjects. The mission will probe structure formation in the early Universe, active galactic nuclei, and star-forming galaxies. At low redshifts (recent cosmic epochs), the mission will focus on the physics and chemistry of the interstellar medium and molecular clouds.

Canadians participated in building important components for two of the three instruments on Herschel. These



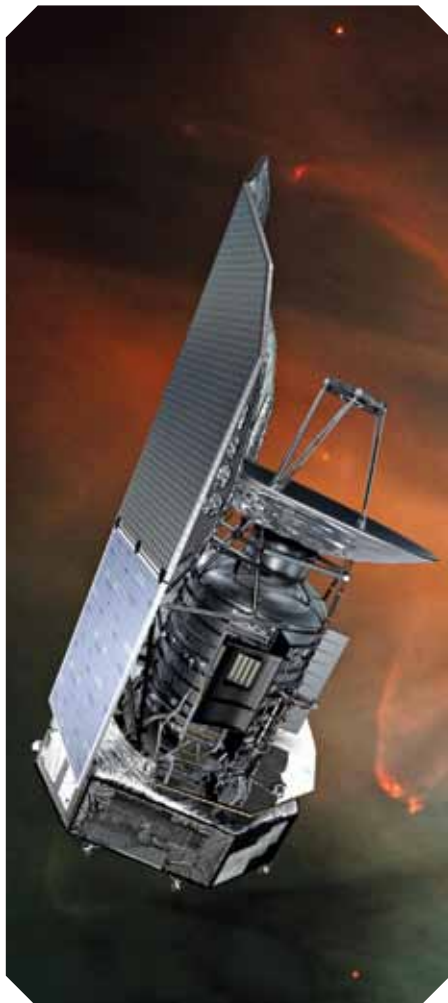


Figure 3-11. The Herschel Space Telescope. The mirror of this infrared space telescope is the largest ever launched into space. [ESA/AOES Medialab; background: Hubble Space Telescope image (NASA/ESA/STScI)]

two instruments were HIFI (Heterodyne Instrument for the Far-Infrared), a high resolution spectrometer, and SPIRE (Spectral and Photometric Imaging Receiver), an imaging bolometer. The Canadian Herschel team includes scientists from (in geographical order) the Universities of Toronto, McMaster, Western Ontario, Calgary, Lethbridge, UBC, Victoria, and also NRC. Herschel instruments were developed in Canadian university labs

and played a key role in building up infrastructure in university-based experimental astrophysics laboratories in Canada, a recommendation of this and the previous LRP.

Canada's contribution to HIFI was the HIFI Local Oscillator Source Unit, which is an essential component of any heterodyne (frequency mixing) instrument. Interestingly, the heterodyne technique itself was invented by a Canadian (Reginald Fessenden) in 1901, so Canada's involvement in this instrument represents a cutting-edge development based on a century-old homegrown innovation. The prime contractor for HIFI is COM DEV in Cambridge, Ontario. The Canadian contribution to SPIRE was a Fourier Transform Spectrometer test facility, and also the FTS data reduction software, both from the University of Lethbridge.

Herschel has an anticipated lifetime of 3-4 years, at which point the helium used to cool the focal plane of the scientific instruments will be exhausted. Launch occurred in 2009 and the mission end-of-life is predicted to occur sometime between late 2012 and spring 2013.

### 3.3 Institutes and Laboratories

#### 3.3.1 HIA

The Herzberg Institute of Astrophysics or NRC-HIA (hereafter HIA) is essentially Canada's national laboratory for astrophysics. Although HIA represents only about three percent of NRC overall, it is unique within NRC: its focus is to enable the advancement of knowledge in the field of Astronomy, and the entire university-based community depends on it. HIA carries out NRC's parliamentary mandate to operate and administer all astronomical observatories established or

maintained by the Federal Government of Canada; it is furthermore Canada's flagship institution for the development of instrumentation for these observatories.

In all respects, HIA is a "shining star" of astronomy in Canada, and has contributed markedly to the current reputation held by Canada as one of the international leaders in astronomy. Without an organization like HIA, Canada could not be a credible and productive partner in major international observatory facilities.

#### *Contributions to Canadian astronomy*

HIA derives funding primarily from a base budget provided by NRC and also from contracts with industry and the Canadian Space Agency. The total funding is about \$36M per year including salaries, which represents about one third of the total budget for Canadian astronomy activity derived from all sources. (Excluding salaries, and excluding the "CSA JWST bubble" [see §6.1], HIA spending is about two thirds of Canadian astronomy spending.) About 40 percent of HIA's budget is allocated directly to offshore observatory facilities. HIA has a staff of about 150 (74% permanent), of which 22% are scientists, 30% are engineers, 31% technologists and computer scientists, and 17% administration and management.

There are two primary divisions devoted to instrument development – one concerned with optical/IR/sub-mm astronomy, centred at the Dominion Astrophysical Observatory (DAO) near Victoria, BC, and the other with radio astronomy at the Dominion Radio Astrophysical Observatory (DRAO) near Penticton, BC. Both of these divisions have leading international reputations for developing innovative cutting-edge instrument designs and for delivering highly reliable instruments on-time and on-budget. The instruments that HIA develops are on a scale that cannot be

duplicated in university labs. In addition, HIA operates the Canadian Astronomy Data Centre (CADC) which provides important services to the community in archiving data from many international telescopes, and by developing techniques for data mining and cloud computing, applicable to both astronomy and many other scientific fields.

Recent projects completed by the DAO Group include ALTAIR, a NIR adaptive optics system for Gemini North, and the successful development and production of the first light (band 3) receivers for ALMA. In addition, this group has made major contributions to the TMT design study and to GPI, a revolutionary Gemini instrument for direct imaging of planets. The DRAO Group built the \$20M ground breaking wide band correlator for the EVLA, and WIDAR processing boards for the eMerlin correlator in the UK. Currently this group is developing designs and prototypes for the SKA antennas and phased array feeds.

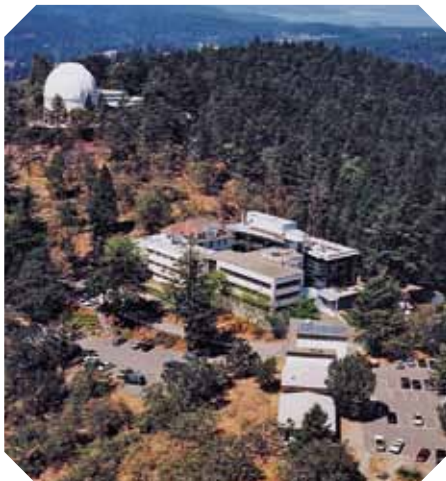


Figure 3-12. The Herzberg Institute of Astrophysics, Victoria, BC. At the right is the office building, and to the upper left is the Plaskett 1.8 metre telescope. [National Research Council Canada]

These and other successes within HIA are attributable to the skills of the scientists, engineers and technologists, and the overall synergy within the organization. These successes bode well to ensure a bright future for HIA, though there are also many challenges ahead.

### *The relationship between HIA and the LRP*

HIA bases its priorities strongly on the LRP, and is the primary resource in Canada for LRP ground based astronomy development work and for much of the instrument design for Canadian space astronomy. Accordingly, HIA has had many successes in its contributions to the LRP, including the accomplishments described in the previous section, and also in the addition of the six PDF positions recommended in the LRP2000 document.

However, beginning with phase 2 of LRP2000 in the second half of the decade, there has been a serious shortfall in resources from NRC for LRP work. This is partly a result of the changing focus of NRC toward strategic commercial priorities and consequently less emphasis on astrophysics. Thus phase II of the LRP has been supported by NRC through “cash management” of its own budget rather than through new funds from the Federal Government. This is not a sustainable situation: new funds for LRP support were, and continue to be, needed. While NRC cannot lobby for the LRP, it would nevertheless be in a better position to secure new funds for the LRP if it were to promote HIA more effectively in its strategic planning documents.

### *Ties between HIA and the university community*

HIA establishes its priorities by consultation with the rest of the astronomy community. Avenues for consultation

include the LRP, the HIA Advisory Board, co-operation with ACURA in the design study of the TMT, and collaboration with universities in radio astronomy activity. However, these ties need to be strengthened and modified as Canada enters the era of involvement in large World Observatories such as ALMA, SKA, VLOT, and JWST. A plan is needed to develop stronger ties and a more formal relationship with ACURA, whose community has a very large stake in such new facilities<sup>7</sup>. The university community is rapidly developing expertise in instrument development and project management, and plays a critical role in training users for the new generation of telescopes. Canadian universities also have an increasing role in projects of modest cost but potentially high impact, such as CHIME and CCAT. Cooperation with HIA would be desirable and mutually productive in these projects. For example, DRAO appears to be an excellent site for CHIME.

### *Ties between HIA and the CSA*

HIA currently receives about \$1M per year from the CSA for the support of activity in space astronomy (e.g. JWST instrument development and operations). However, stronger cooperative links would be beneficial in the coming era as space astronomy becomes more and more an integral part of astronomy planning. To effectively coordinate their respective roles in space astronomy, NRC and CSA need to find a way to integrate their activity to produce a unified and synergistic management of space astronomy. For reasons stated earlier, ACURA would need to be included as a partner in any new form of cooperation between NRC and CSA (see also §6.3).

In conclusion, for the LRP to succeed, it will be important that HIA be provided with the resources necessary to maintain its leading edge status internationally, and

<sup>7</sup> See Section 6.3 for a proposed new governance model for HIA that involves ACURA.

to respond to the increasing demands placed on it by new facilities such as ALMA, VLOT, and later the SKA. These demands include the need for facility support, for skilled staff to design and build innovative instrumentation, and for staff to maintain the CADC at the forefront of data archiving and data mining. As noted in the section on Governance, the LRPP recommends that NRC be proactive in exploring ways to increase the level of cooperation with ACURA and the CSA in order to respond to the needs of all stakeholders in astronomy. Finally we note that HIA needs to be promoted more strongly in the NRC strategic plan befitting HIA as one of its most internationally recognized institutes.

### 3.3.2 University-based Experimental Astrophysics Laboratories

Experimental astrophysics encompasses a broad range of multi-disciplinary and complex activities covering the full electromagnetic spectrum, including end-to-end design and construction of state-of-the-art astronomical instrumentation, technology development, and signal processing. The success of a nation in astrophysics relies heavily on having a strong base in this field, supplemented by expertise at all levels: academia, industry and large national laboratories such as HIA. Universities play a crucial role in this field by seeding new ideas, undertaking R&D, contributing to national/international projects, and, most importantly, by training the essential highly-qualified personnel for universities, industry, HIA and offshore facilities. University-based Canadian astronomers are actively involved in an impressive array of exciting ground- and space-based projects (see Table) spanning the full electromagnetic spectrum. Many of these projects take place in close collaboration with HIA, industry and international institutions.

### University activities in Experimental Astrophysics and Astronomical Instrumentation

| Waveband      | Institutions   | Project/Facilities                                  |
|---------------|----------------|---|
| Radio         | U. Calgary     | ALMA, EVLA, SKA, Arecibo                            |
|               | UBC            | CHIME, Arecibo, GBT                                 |
|               | McGill U.      | CHIME   |
| Far-IR/Sub-mm | U. Lethbridge  | Herschel, SCUBA-2/FTS-2, SPICA, TMT, GMT, E-ELT     |
|               | U. Waterloo    | Herschel, SCUBA-2, CCAT, FIRI, SPIRIT               |
|               | UBC            | SCUBA-2, ACT, CLOVER, SPIDER, BLAST                 |
|               | U. Montréal    | SCUBA-2/POL-2                                       |
|               | UWO            | SCUBA-2, CSO  |
|               | U. Toronto     | BLAST, BLAST-POL, SPIDER, BOOMERANG                 |
|               | McGill         | South Pole Telescope, APEX-SZ, EBEX, Polarbear      |
| Optical/IR    | U. Montréal    | OMM, CFHT, Gemini, JWST, NTT, WHT, EMCCD controller |
|               | Laval          | OMM, CFHT, Gemini                                   |
|               | U. Toronto     | Keck, Palomar, Gemini, TMT, MOST, BRITE             |
|               | U. Victoria    | Subaru, TMT   |
|               | UBC            | TMT, MOST   |
| Ultraviolet   | Calgary, Laval | UVIT  |
| Gamma Rays    | McGill         | VERITAS, AGIS, Compton Scattering Telescope         |

The creation of centres for experimental astrophysics within Canadian universities was a recommendation of the last LRP that was echoed by the MTR. (See §3.3.3 for a discussion of one of these centres, OMM/LAE.) While experimental astrophysics has grown very significantly in the last decade, especially through new faculty hires across the country (Laval, McGill, Montreal, Victoria, Toronto, Western), the motivation for creating such centres or networks is even more acute now, especially for supporting technical staff on a longer-term basis. Funding for experimental astrophysics over the past decade came from CFI, CSA, NSERC and universities; this funding has enabled a wide range of ground- and space-based projects, amounting to more than \$50M. While these funds have seeded the creation of several, albeit relatively small,

teams in experimental astrophysics across the country, these funds are not renewable by nature (except for faculty positions); this makes it difficult to maintain a critical mass of highly-qualified personnel over relatively long periods. A stable core of expertise is indeed an important asset: it allows groups to remain competitive on the international scene for attracting major instrumentation contracts, and it enhances the flow of novel ideas that seed exciting new projects. Maintaining a critical mass of core expertise within one's team constitutes the main challenge facing the Canadian experimental astrophysics community in this decade. Another challenge is integrating technical expertise and knowledge that is currently dispersed over several universities into a more cohesive national work force.



The University of Toronto has recently established the Dunlap Institute (DI) for Astronomy and Astrophysics, funded through the sale of the University's David Dunlap Observatory. The Institute has just appointed its first Director and is actively recruiting new faculty. The Institute will essentially run in parallel with the University's existing Department of Astronomy & Astrophysics and CITA, and is ultimately expected to have comparable resources to both of these. The Institute is expected to invest in the development of astronomical instrumentation for world-class observatories, and to foster major national and international research collaborations, with a strong emphasis on promoting interactions among astronomers engaged in observation, experimentation, simulation and theory, as well as in both training and outreach.

The LRPP commends the various stakeholders (universities, CFI, CSA, NSERC and provincial agencies, as well as privately funded institutes) for the significant investments made towards experimental astrophysics in the last decade.

## Recommendation 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.*

### 3.3.3 Small Telescopes in Canada

Small telescopes play an important role in science, in student training, and in instrumentation development. The number of small telescopes used for professional research in Canada has been eroding in the past decade. With the demise of research funding for the University of Western Ontario telescope and the David Dunlap Observatory, there remain three optical 1-2m class telescopes in operation for professional use in Canada: the 1.2m telescope and 1.8m (Plaskett) telescope of the Dominion Astrophysical Observatory (DAO), both located in Victoria at HIA; and the 1.6m Observatoire du Mont-Mégantic (OMM), in the eastern townships of Quebec. The Dominion Radio Astrophysical Observatory (DRAO) operates small radio telescopes.

#### DAO telescopes

The DAO telescopes, owned and operated by NRC-HIA, are equipped with high-resolution optical spectrographs, a spectropolarimeter and an imager; they are used for a wide range of scientific programs (including radial velocities of stars, ISM, comets, magnetic and variable stars, and determining orbits of potentially hazardous near-Earth asteroids). Thirty per cent of the 1.2m telescope time is now used in an automated (robotic) mode. Several large programs have been carried out in direct support of CFHT, Gemini and MOST. For example, the McKellar spectrograph on the 1.2m telescope is being used for identifying relatively young stars in support of a forthcoming large observing campaign with the Gemini Planet Imager. These stars are inherently bright, hence perfectly matched to small telescopes such as DAO's.



Figure 3-13. (Left) The 1.83 metre Plaskett telescope of the Dominion Astrophysical Observatory (DAO). [Eric Chisholm] (Right) The 1.2 metre telescope of the DAO. [Eric Chisholm]

The DAO telescopes are used as testbeds for AO prototyping and for other university-based instruments such as the electron multiplication CCD imager developed jointly with HIA staff and a McMaster PhD student. A very inexpensive circular polarization module has been implemented on the 1.8m telescope's Cassegrain spectrograph, enabling longitudinal magnetic field measurements with good precision. This led to a large complementary program on the Plaskett telescope in support of the CFHT large program MiMeS aimed at studying magnetic properties of relatively massive stars. DAO is anticipating the development of a fibre-fed IFU for the Herzberg spectrograph that could pave the way to eventual robotic operation of the Plaskett telescope. More on instrumentation activities at DAO can be found in §3.3.1.

The subscription rate exceeds 1 for both DAO telescopes. A dozen peer-reviewed papers are published every year based on observations from both telescopes, with a positive trend since the input of LRP money in the last decade.

The DAO telescopes are the focus of important outreach activities, together with a visitor centre ("Centre of the Universe") located on-site and developed by NRC-HIA in response to LRP2000. Local efforts focus on offering curriculum related programs for schools, summer public viewing, and leadership in provincial and national outreach (e.g., National Science and Tech Week, Marsville) using astronomy to help youth and the general public to gain an improved appreciation of the role of science in our society. These programs annually reach approximately 10,000 through on-site visits and another 10,000 through off-site activities, including over the Web.

## OMM and LAE

L'Observatoire du Mont-Mégantic (OMM) is the only university-based research telescope in operation in Canada; it is jointly managed by U. de Montréal and U. Laval. Thanks to judicious site selection in the 1970's, and a significant local effort to control light pollution, OMM still enjoys a very dark site.

The OMM is equipped with a wide palette of state-of-the-art optical/infrared instruments: wide-field optical/IR imagers, optical and near-IR spectrographs, an optical polarimeter, an optical Fabry-Perot imager employing a photon-counting CCD, and a visible imaging FTS unique in the world. (Very few 1-2m class telescopes in the world offer such a wide variety of instruments.) The OMM instrumentation is used for a wide range of scientific investigations, many of which cannot be achieved on larger offshore facilities (CFHT and Gemini). OMM has provided a complementary data set in support of

large international programs – e.g. H $\alpha$  imaging for the Spitzer Infrared Nearby Galaxies Survey, polarimetry data for the Herschel Open Key Program DEBRIS. The OMM wide-field IR imager has been (and is still) used both on OMM and on the 1.5m CTIO telescope in Chile to conduct a large infrared proper motion (SIMP) survey aimed at identifying new brown dwarfs and other rare objects such as young low-mass stars. This program has fed many spectroscopic follow-up programs on Gemini. Of the ~900 L and T dwarfs discovered so far, more than 10% were unveiled through the SIMP survey.

The subscription rate of OMM varies between 1.5 and 2. Since December 2009, OMM offers a queue mode to the community. This mode is quite popular and growing; approximately 20% of the OMM observing time is now in this mode; 80% of the queue mode requests are from external users in Canada, the US, the UK and France. In the spirit of



Figure 3-14. The 1.6 metre telescope of the L'Observatoire du Mont-Mégantic (OMM). [L'Observatoire du Mont-Mégantic]



the OMM training mandate, the queue mode is operated by graduate students.

OMM is also an important platform for instrumentation development. Since 1999, some of the OMM personnel are integrated within a multi-institutional (U. Laval, McGill U., U. de Montréal) parallel structure: the Laboratoire d'Astrophysique Expérimentale (LAE) focused on experimental astrophysics activities beyond OMM instrumentation. The LAE is an active player in the development of CFHT, Gemini and JCMT instrumentation as well as balloon-borne sub-mm experiments and high-energy experimental astrophysics. Notably, the development of high-contrast differential imaging techniques was pioneered at U. de Montréal and tested on OMM; these techniques are now extensively used worldwide on 8-10 metre telescopes. LAE is a world leader in the development of photon-counting CCDs, benefitting from OMM as a testbed facility.

OMM/LAE attracts many students. In the last decade, U. de Montréal and U. Laval alone graduated a total of 42 PhDs, of which 33 were observational, with 55% of those (18) in projects involving OMM data. Most CFHT Canadian resident astronomers graduated from U. de Montréal and U. Laval. The OMM/LAE supports an average of ~15 MSc/PhD per year. An average of one peer-review paper is published each month based on OMM observations; this number nearly doubles when instrumentation-related (SPIE) papers are included. OMM/LAE received significant investments in the last decade from CFI: \$4.7M in 1999 and \$11.7M in 2009 for new OMM instrumentation (a telescope upgrade and a new off-shore facility instrument, SITELLE – see §3.1.1).

OMM is located within a provincial park whose main attraction is a visiting centre, the Astrolab, located at the bottom



Figure 3-15. The Dominion Radio Astrophysical Observatory Array Telescope, outside Penticton, BC. [Andrew Gray]

of the mountain. Despite its remote location to main urban centres, the Astrolab attracts more than 20,000 visitors each year. The Astrolab features an exposition, a multi-media room and a visit of the OMM telescope. The Astrolab also owns a small 60cm telescope on the mountain for outreach activities. The activities of the Mont-Mégantic park feed about \$3M/yr into the local economy, largely contributed by the attraction of the Observatory.

## DRAO

HIA-DRAO operates three small facilities – the seven-antenna interferometric Synthesis Telescope, the single-antenna 26m telescope and a pair of small Solar Radio Flux Monitor Telescopes. These are all historic and productive telescopes that have been operating at DRAO for a long period of time. In recent times the Synthesis Telescope and the 26m telescope have been associated with a series of impressive, large-scale surveys.

The Canadian Galactic Plane Survey (CGPS) of the outer Milky Way Galaxy at 1420 MHz (neutral hydrogen) and 408 MHz was a university-led, international consortium project to study the ecology, structure and dynamics of the Interstellar Medium. Its success leveraged Canadian leadership of the International Galactic Plane Survey, which produced a data set of the complete Milky Way galaxy using the CGPS and observations from the VLA and the ATCA.

The 26m telescope has been used to map the northern sky in linear polarization at 1420 MHz. These excellent data surpass previous surveys by an order of magnitude in sensitivity and two orders of magnitude in coverage. This is of significance to Galactic science projects; the data are being actively used for deconvolving the polarized foreground through which the Planck satellite views the Cosmic Microwave Background.



Two very small antennas are associated with the Solar Flux Monitor program; these antennas monitor the Sun daily at a wavelength of 10.7 cm. This operation is part of the Canadian Space Weather system, a collaboration among NRC, CSA and NRCan. This is the longest running radio astronomical observing program anywhere in the world, with 64 years of continuous data. These are critical data, distributed by NRCan and used widely by industry, space agencies, and defence for monitoring the state of the Sun, and ensuring the long-term health of the now-extensive satellite network.

The research and development programs conducted with these telescopes, primarily the Synthesis and 26-m telescopes, is responsible for the expertise within DRAO and Canadian universities that now fuels development work on the SKA.

### Conclusion

The LRPP recognizes the importance of small telescopes as excellent platforms for student training and instrumentation development. Small telescopes provide a critical testbed for prototyping instrumentation, the fruits of which ultimately benefit international facilities. They are natural foci for education and public outreach activities. Securing funding for operation is the main challenge facing small telescopes.

### Recommendation 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.*

### 3.3.4 CITA

The Canadian Institute for Theoretical Astrophysics (CITA) hosts one of the largest concentrations of theoretical astrophysicists in the world and is recognized worldwide as an outstanding research institute with high visibility. Though the primary focus of CITA is to train PDFs in theoretical astrophysics (11 were directly MRS-funded in 2009), CITA faculty and PDFs also supervise graduate and undergraduate students (28 in 2009), interact and collaborate with many visiting faculty from around the world (155 in 2009), and support conferences, workshops and seminars both at CITA and across Canada. CITA also supports a National Fellow PDF program that funds half the cost of six Fellows resident at universities across Canada.

CITA's external funding comes from many sources, but especially NSERC (through an MRS grant), and through CIFAR (support of faculty). Both of these are discussed in §6.4.1.

Another notable CITA contribution to Canadian astrophysics, in addition to its scientific contributions and visibility, is its training of future Canadian theoretical astrophysics faculty. To date 23 former CITA PDFs or CITA National Fellows are in tenure track or tenured positions in Canada. This demonstrates CITA's success in attracting talent to Canada in the long-term.

CITA is also at the forefront of large-scale astrophysical computation, playing a major role in simulations of cosmic structure formation. CITA intends to expand in the area of high-performance computing. CITA is continuing to push the boundaries of high-performance computing, through SciNet and, most recently, by installing a GPU-based computer cluster capable of 100 teraflop speeds, for work

in numerical relativity, magnetohydrodynamics, and N-body simulations.

CITA is, simply put, an outstanding centre of scientific excellence. Its impact would be enhanced by expanding the strong linkages with other institutions in Canada, for example through expanding the National Fellow program at other universities. The CITA National Fellows program supports theoretical research by providing six 50%-funded PDFs. The program is supported as part of an NSERC MRS to CITA, and is comparatively inexpensive because it leverages funding from other avenues. Adding a further four National Fellows would require adding only 12% to the base MRS while almost doubling the current support. See also §6.4.1 and §7.3.

### Recommendation 9

*The LRPP recommends that CITA's NSERC support be increased by 12%, 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 4 new PDFs to the CITA National Fellows Program.*

### 3.3.5 Perimeter Institute

The Perimeter Institute was founded by private philanthropy in 1999 to address some of the deepest questions in theoretical physics, with a specific focus on quantum theory and space-time. The Institute began operations in 2001, and now houses 11 faculty and 45 PDFs, with 10 cross-appointed associated faculty visiting on a regular basis. In addition, a program of distinguished research chairs has brought in a number of internationally renowned researchers to the Institute for 1-2 month periods.

The PI has growing expertise in cosmology, ranging from quantum cosmology to classical cosmology and gravitational theory, with six faculty and associated faculty working in these arenas. Over the coming years an increase to 25 faculty and 16 associated faculty is anticipated. As part of the growth plan, the Institute plans to become more involved in observational and experimental projects. It is anticipated that links will be established to Planck, VISTA, VLT, SKA, astro-particle projects such as SNOlab, and the gravitational wave detectors LIGO and LISA. The PI has forged a series of connections with other institutions across the country. Perhaps most notable is the connection to CITA, which has resulted in a series of PI-CITA joint research events. The PI is also aggressively increasing its international presence by starting a Masters program that will attract some of the best students around the world to Canada. This program should provide a significant supply of well-trained students to the Canadian research community.

The PI has also invested heavily in outreach programs. A series of lectures is broadcast regularly on provincial cable television, and two science festivals, EinsteinFest (2005) and Quantum to Cosmos (2009) have been organized. But perhaps most significant is the investment in teacher training, the EinsteinPlus Teacher Workshops, and the preparation of a new generation of teaching materials on difficult subjects such as cosmology and dark matter. Future modules in various areas of astrophysics are anticipated.

The LRPP recommends strengthening ties between the astrophysical community in Canada and the Perimeter Institute, to bring together diverse expertise and build on our strengths in order to make major progress on some of the greatest challenges facing science today. PI

personnel should be encouraged to participate in CASCA meetings, and continue interaction with CITA. We look forward to further linkages which will develop as PI becomes more involved in experimental projects.

## 3.4 Computational Resources, CADC and Networks

Computation is a fundamental enabler of astronomical research progress: the computer is as important as the telescope. Usage of computing by astronomers across Canada reflects this reality. In 2009 20% of the large-scale computation and storage requests received by Compute Canada came from astronomy and astrophysics projects, despite the number

of researchers in this field being approximately 0.5% of researchers in Canada.

In the decade since the last LRP, data rates from telescopes have grown exponentially (Figure 3-16). At the same time Canada's digital infrastructure has evolved. The NRC-HIA's Canadian Astronomy Data Centre (CADC) has added four additional staff as a result of LRP2000. Funding from the CFI and provinces has injected \$30M per year into HPC through Compute Canada (CC), while the federal government has invested \$24M per year into the national research network organization, CANARIE. Provincial ORANs have also been funded to upgrade the provincial research network backbone; in Ontario alone \$32.3M was invested in the ORION ORAN. This new funding has addressed many of the issues highlighted in LRP2000.

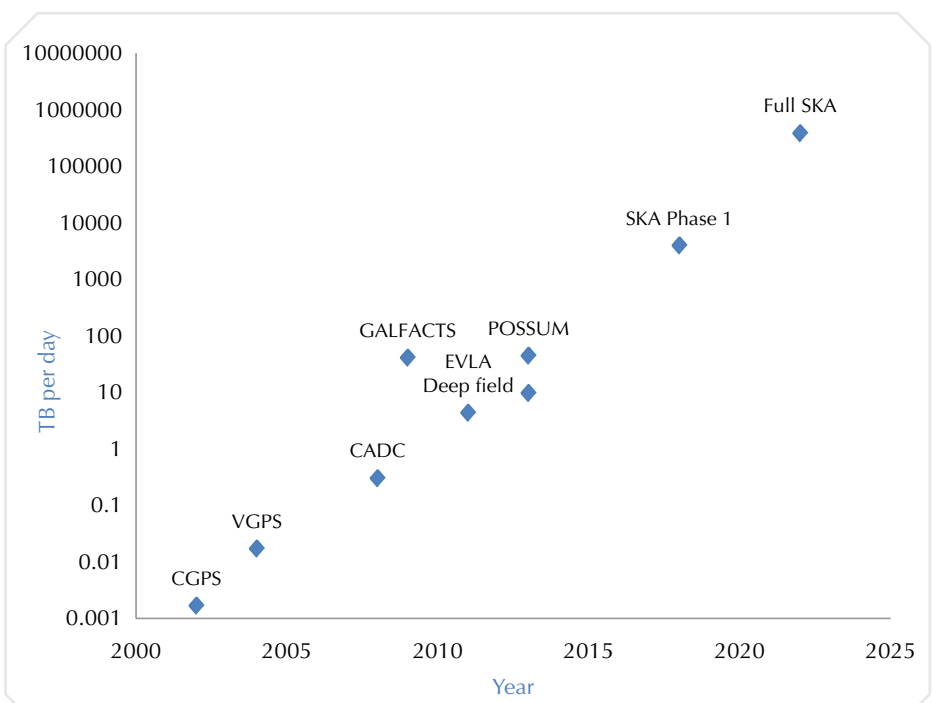


Figure 3-16. Growth in data rates from a number of radio telescopes, and also for CADC. [A.R. Taylor, U. Calgary]

However, preparing for the science of 2020 presents new challenges. A number of planned facilities, such as ALMA, LSST, and SKA, will produce PetaByte to ExaByte datasets. Consequently, there is growing interest in the field of *astroinformatics*: the science of astronomical data analysis of vast datasets. However, an increase in fidelity of data demands an equivalent advance in theoretical understanding. To meet the challenge posed by upcoming observations, simulations must grow in size, and become more sophisticated in terms of the physics modeled.

It is equally important to emphasize that the different aspects of digital infrastructure, including algorithms, tools, HPC resources, rapid-access large-scale storage and high performance networks, all play important roles. Overemphasis on one aspect, say HPC at the expense of sufficient storage, or network services without compute resources, will lead to a fundamental imbalance.

## Compute Resources

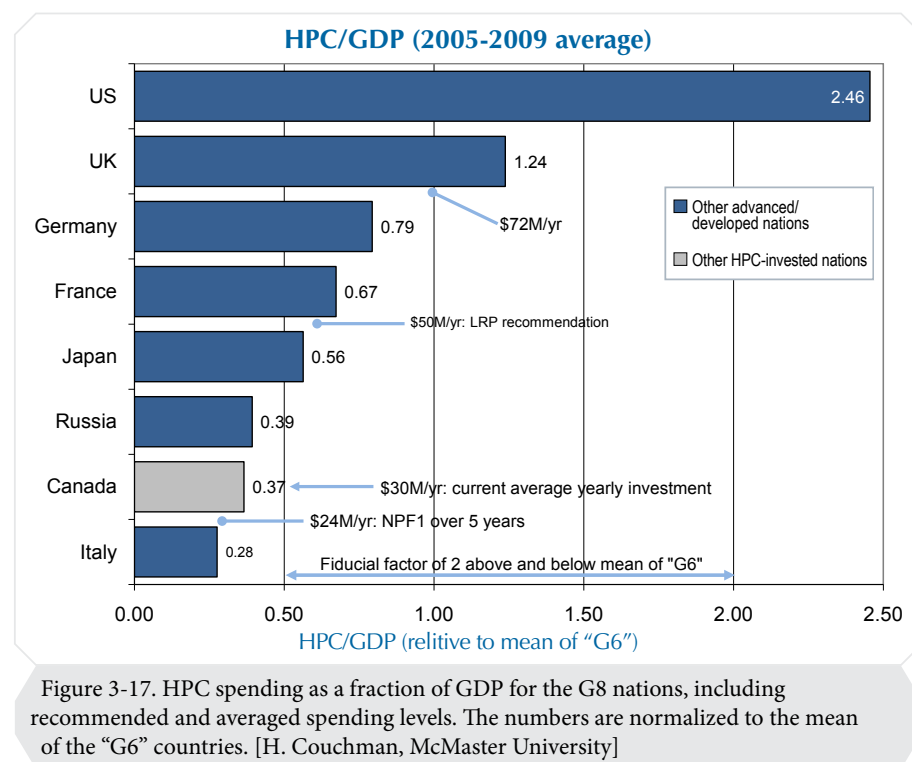
CC was formed in 2006, to provide a single “National Platform” for HPC in Canada. It coordinates HPC facilities and support personnel at the national level, while at an operational level facilities are managed by regional consortia. From west to east these are WestGrid, HPCVL, SHARCNET, SciNET, CLUMEQ, RQCHP and ACEnet. Since 2002 the average funding to CC, including provincial matching of CFI grants, has amounted to \$30M per year. Averaged across a national user-base of at least 4000 researchers, this amounts to \$7500 per user per year. Compared with expenditure on the Top 500 list of supercomputers by the G8, estimated by assuming a fixed cost per computational operation, this is 1/3 of the average, as a fraction of relative GDP (see Figure 3-17).

The HPC ecosystem has been portrayed by many observers in a pyramid form, with national supercomputing centres at the top, mid-level departmental- and university-level servers in the middle, and a base-layer of PCs at the bottom. While there has been significant investment in mid-level computing, it is noteworthy that only in 2009 did Canada have a system large enough to enter into the Top 20 of the Top 500 list of supercomputers, namely the SciNET consortium at the University of Toronto. Thus, only in 2009 did we add a top level to the pyramid.

Despite the significant investment in CC, a number of consortia are still running equipment that is five years old and far behind the current state-of-the-art. Given that current government projections include a roll-back of CC funding to a \$24 M/yr funding level, this is a great concern for all data- and compute-intensive sciences in Canada. Growing demands of data and a scaling back of

funding suggest that a critical collision between researcher’s needs and available resources is coming.

Astronomy’s reliance on computing, both for data analysis and simulation, makes it especially vulnerable to lack of resources. A gross rule of thumb for data-analysis capabilities is that every byte of data should be matched by an equivalent number of flops, i.e. petabytes of data requires petaflops of computing to analyze. The SKA stands out in this regard as a facility that will depend as much on computing as it does on telescope hardware. Current design estimates put the central computing facility requirements at the order of 1 Exaflop, while regional facilities, which potentially Canada could host at the end of the decade, will require around 0.1 Exaflop. Thus, while HPC is already an indispensable component of astronomy infrastructure, it will become even more so in the future.





For simulation work, the vast dynamic range and physical complexity of astrophysical systems continue to present enormous computing challenges. In the past decade Canadian researchers have contributed to major advances in planet, star and galaxy formation calculations (as noted the research highlights in §2.2) using HPC facilities. Reaching the level of fidelity required by future observations is anticipated to focus attention closely on the field of radiative transfer, which presents one of the most significant computational challenges in astrophysics while being one of the most important physical processes in the Universe. Other specific scientific problems awaiting petaflop level computing include modelling molecular cloud evolution within galaxies, black hole collisions, 3D stellar structure, MHD simulations of star formation and cosmological reionization and there are many more. Progress in these fields will depend strongly on the continued provision of a Tier 1 computing facility in Canada.

While this section has thus far focused on hardware, software support and research, which includes funding for development consultants, is a key aspect of effective use of HPC facilities. The CFI/provincial investment in hardware has not been matched by a similar investment in personnel. For example, the Top 20 system installed at SciNET is equivalent in size to the UK HECToR system. HECToR funds 20 consultants, for an average of 25 users per consultant, while SciNET can only afford three consultants, for an average of 106 users per consultant.

The recently announced Major Science Initiatives (MSI) program is a strongly welcomed new funding source for addressing this operational shortfall. However, without a strong commitment to maintain funding of CC at sustainable levels for both hardware and software, the



Figure 3-18. View of computers in the SciNET data centre. [SciNet/Chris Pratt – IBM]

capacity of computational infrastructure in Canada may well not meet the needs of its researchers. The following recommendation proposes doubling Compute Canada funding (i.e. raising it to 2/3 the average of G8 countries) with software support scaled to 10% of the US Cyberinfrastructure software institutes program, and emphasizes a Tier 1 facility should be provisioned on a continuing basis.

### **Recommendation 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.*

While the pyramid view of the HPC ecosystem has worked for many years, it may not describe accurately the future evolution of computing resources. The destabilizing technology is “cloud computing”. In this computing paradigm computational jobs described on a desktop computer are distributed across a network to computing centres in an essentially invisible fashion. Google searches are the archetype of this approach: these searches are data intensive (sorting through billions of web pages) to generate a short list of results. However, the technique is potentially far more powerful and adaptable than just searching. The CANFAR astronomical data-analysis platform utilizes cloud computing to enable astronomers to develop custom analysis tools for their data.

Google’s immense computing farms now dwarf those of the largest HPC system in the US. The future of data intensive computing appears likely to follow the cloud model, which strongly suggests future investment will need to go beyond that

nominally associated with HPC. The SKA regional centres will likely be strongly dependent on this computing model.

## Recommendation 11

*The LRPP recommends that Compute Canada move to fully support users with cloud computing requirements.*

## CADC

By providing central data archiving and management services, the CADC plays a critical role in Canadian astronomy. Its mandate has grown significantly beyond the original purpose of providing access to HST data, and it now serves and manages data for 19 projects, including the HST, Gemini, CGPS, CFHT, and JCMT. It also hosts the Canadian Virtual Observatory, which links together multi-wavelength data through an international collaboration known as the International Virtual Observatory Alliance.

In the past decade the CADC has responded impressively to a number of significant challenges in data management and archiving. Ignoring archives that are widely replicated, such as the Digital Sky Survey, usage has increased by a factor of 20, from 151 distinct users in 1999 to over 2900 by 2009. The increase in users has also been matched by a two order of magnitude increase in data downloads since 1999, with 2009 downloads exceeding 100 TBytes of data (see Figure 3-19).

This growth reflects the increasing importance of data archives and also the significant international confidence in the CADC, which has resulted in it being the sole provider of the Gemini Science Archive. In addition, CADC staff have made contributions to ESO's Science

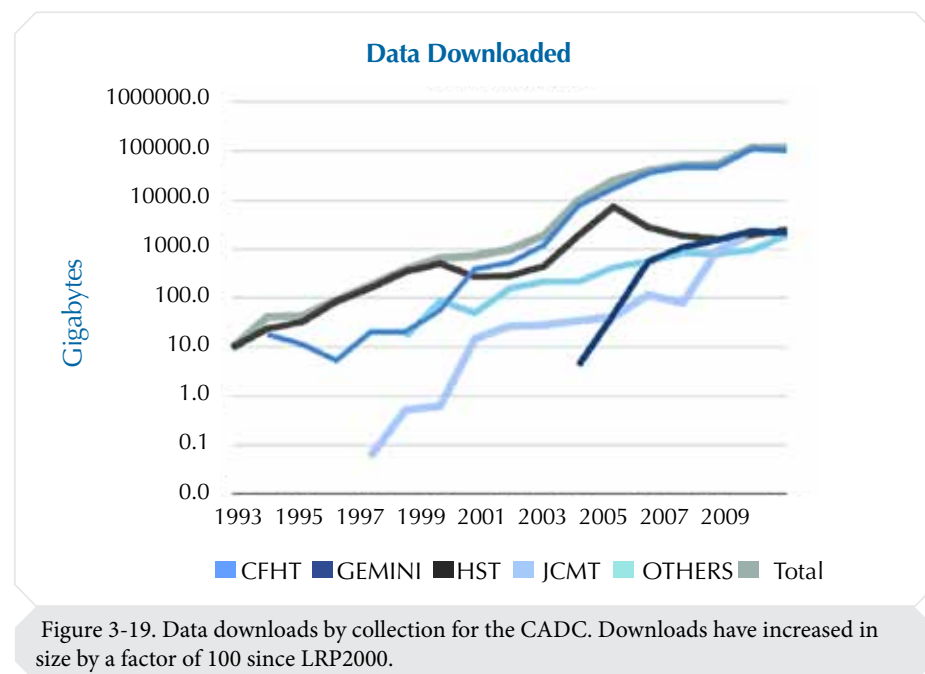
Archive Facility and are actively consulting on data management in the ALMA project. The continued international demand for input from the CADC speaks to both the talent of the individuals in the group and the world-leading expertise that has been developed therein.

All the recommendations of LRP2000 were met by the CADC. In fact, the unanticipated increase in data demand and archive growth has required staffing levels to increase beyond those recommended at the start of the decade. The current staff of 20 span specialties from astronomy through to computer science, a mix that reflects the science orientation of the CADC and its technical complexity. It is, nonetheless, a mix that works effectively, particularly since science decisions remain the primary driver of CADC internal policy.

Funding of the CADC is achieved by a mixture of capital (25%), external fees or contracts, and an annual transfer (12%)

from CSA, for a total budget of \$2M per year. At present 60% of staffing costs are covered by external revenues, such as the Gemini archive and the CANFAR contract with the University of Victoria. Despite the CADC's success in securing this funding, 35% of staff contracts end in 2011. Future staffing thus entails significant uncertainty. Hardware costs were also handled internally until recently. However, the start of the CANFAR project signalled a transition to a reliance on CC infrastructure, which will tie the success of the CADC to the success of CC.

Despite the growth and broadening of the CADC to meet increasing data requirements, some challenges that were highlighted in the MTR still remain. In particular, the MTR recommendation of establishing end-to-end data management policies for observatories has not been met. With ALMA (late 2011 operations start) being the first of the "data intensive" observatories, the need for establishing a Canadian data management policy is



becoming urgent. In the longer term, the SKA in particular will place exceptional demands on processing and storage that need to be considered in the wider national picture.

### **Recommendation 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), CSA, and CASCA should be formed to address this point, particularly focusing on the needs of the “world observatories”.*

While data storage and access needs are pressing, the development of analysis tools is equally important. Multi-terabyte datasets are already changing the way analysis is conducted. No longer is it possible to apply simple linear I/O techniques: collaborations with specialists are becoming necessary (e.g. Microsoft’s Dr Jim Gray and the SDSS project) and astroinformatics is building momentum. This is particularly relevant to the LSST project, where data mining the whole sky is anticipated to yield new discoveries in time-domain astronomy.

The SKA will present even larger challenges. Ultimately, the development of data analysis tools will prove to be as important as the building of the facilities themselves. CANFAR is a good first step in this direction, but more development is needed.

### **Networks**

As science becomes increasingly data intensive, network bandwidth will need to grow. In particular, cloud computing infrastructure, where the precise location of calculation and data are abstracted in the user interface, depends critically on network bandwidth and availability.

Management of networks is a complex issue that spans local, provincial and federal jurisdictions. The 10Gb/s national backbone is provided by CANARIE, and, with some exceptions, this network connects the provincial ORANs together. The ORANs then connect to over 257 colleges and universities, as well as hospitals and CEGEPs. The connection from the campus ORAN gateway to the researcher’s desktop falls to campus IT departments. Across Canada, 46 universities participate in the CUCCIO organization, providing a potential for coherent policy on campus IT support. This network is critical: over 40,000 researchers and almost 750,000 students depend on it.

Networking is only as good as the weakest link in the chain. For many researchers the so-called “last mile” of networking from the campus gateway to their PC is often where the bottleneck occurs. Even the CADC is currently ill-equipped, with a single 1Gb/s network connection. For many researchers, moving 100’s of GB’s of data requires waiting several hours. While some large-scale data projects have developed solutions, the infrastructure is not always generally available. Looking to the future, unless the necessary investments in last-mile infrastructure are made, network bottlenecks will block discovery and innovation in the era of data intensive science.



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



## 4. New Ground-Based Facilities

Advances in observational astronomy depend critically on access to the best and newest facilities. Here we look at the new facilities that Canada must be involved with over the next decade if we are to preserve our excellence in modern astronomy. We divide our discussion of new facilities according to cost. Very Large Facilities<sup>8</sup> are defined as those with total cost (to Canada) greater than \$100M (or a total cost greater than \$500M for all partners), large-scale facilities \$30-100M, medium-scale facilities \$5-30M, and small facilities less than \$5M. The Square Kilometre Array (SKA) is a special case: by all definitions it is a Very Large Facility (and is discussed as such below), but most, or perhaps all, of its construction costs will fall in the next decade, so that its funding impact in 2010-2020 is medium-to-large scale, depending on its construction timeline.

### 4.1 Very Large Facilities

By our definition above, only one Very Large Facility presently exists: the European Southern Observatory's Very Large Telescope (VLT). In the future, a number of Very Large Facilities are now under construction or in the planning stages:

- ALMA (see §3.1.3), which is approaching completion
- TMT, an optical-infrared Thirty Meter Telescope (discussed in §4.1.1), proposed for Mauna Kea, Hawaii. The partnership includes Canada, U. California, and CalTech, with strong interest expressed by China, India, and Japan.

- GMT, the Giant Magellan Telescope, a 24.5 metre optical-infrared telescope proposed for Las Campanas in Chile. The project is led by the Carnegie Institution, partnered with several US universities and international organizations.
- E-ELT, the European Extremely Large Telescope (discussed in §4.1.1), a 42 metre optical-infrared telescope proposed for Cerro Armazones in Chile, and led by the European Southern Observatory
- SKA, the Square Kilometre Array (see §4.1.2), a very large radio telescope with a large international partnership including Canada

These are all facilities which are too large for a single nation to build on its own, and which generally involve international partners<sup>9</sup>. Access to Canadian funding for such facilities requires a direct approach to Industry Canada, and to the federal budget process.

Why do Very Large Facilities matter? Each age has its own forefront astronomical facilities, and history shows that researchers with access to these have an overwhelming advantage over their peers. This precedent begins with Galileo and extends in an unbroken chain all the way to the present. Canada's rise as a leading astronomy nation can be traced to its partnership in the best large telescope of the late 20th century, CFHT. European ground-based astronomy's rise to its present position is directly traceable to the construction of the best large telescope of the early 21st century, the VLT.

And the Hubble Space Telescope, which is arguably one of the most productive telescopes of all time, is also one of the most expensive.

Canadian astronomers are heavily involved in the development of two Very Large Facilities: a Very Large Optical Telescope (VLOT), and the Square Kilometre Array (SKA); both are discussed below, and both are considered of extremely high priority. The reported construction timelines for these projects are 2012-2016 (VLOT) and 2016-2019 (SKA Phase 1). The projects are scheduled closely in the same decade but are phased to not overlap in time. The relationship between the two projects and the implications of their timing are considered further in §9, "Summary of Priorities".

#### 4.1.1 Very Large Optical Telescopes

The next stage in the growth of ground-based observational astronomy is participation in a 30m-class Very Large Optical Telescope (VLOT<sup>10</sup>). As noted earlier, three proposed VLOTs (TMT, GMT and E-ELT) are being considered by various international consortia. Canadians remain active participants in TMT, and continue to be involved in discussions with ESO regarding possible participation in E-ELT (see Appendix G).

<sup>8</sup> Alternate terms in use include "Megafacility" and "World Observatory".

<sup>9</sup> The Large Synoptic Survey Telescope, LSST, an 8m survey telescope, is also a Very Large Facility from cost considerations, but is a US-led, rather than international, project.

<sup>10</sup> Alternate acronyms include ELT (extremely large telescope) and GSMT (giant segmented mirror telescope). "ELT" is often confused with E-ELT (the ELT being developed by ESO); GSMT is used in the US to refer to the TMT or GMT projects.



Figure 4-1. Design drawing of the dome of the Thirty Meter Telescope (TMT). The dome structure has been designed by a Canadian company (DSL, Port Coquitlam, BC). [copyright TMT Observatory Corporation]

### Science Case for a VLOT

The use of adaptive optics, a key component of all VLOT designs, makes a 30 m VLOT approximately 200 times more powerful than an 8 m (for a small field). Canada's participation in a VLOT is therefore essential if we are to be a significant player in 21st century astronomy. The science drivers for participating in a VLOT project are in fact all of the science questions discussed in §2.1; a VLOT will provide new observational opportunities in essentially every field of astronomy and astrophysics. Detailed science cases for a VLOT are compelling<sup>11</sup>, and we briefly present only a few here:

1. *Extrasolar planets and the Search for Life* – VLOT-class telescopes will allow us to characterize the atmospheres,

and to look for signatures of life, on planets orbiting other stars.

2. *First Light* – VLOT will provide us with a spectroscopic capability to explore the epoch at which the first stars and galaxies formed from primordial hydrogen and helium created by the Big Bang. VLOT would work synergistically with the James Webb Space Telescope (JWST) in this area, with JWST providing the targets for detailed study with a VLOT.

3. *Super-massive Black Holes* – VLOT will lead breakthrough investigations of the nature of super-massive black holes at the centres of galaxies. VLOT's combination of high spatial and spectral resolution will allow us to probe black holes at cosmological distances. VLOT will also allow

us to greatly expand our understanding of the black hole at the centre of our own galaxy, and even to test general relativity using our galaxy's central black hole as a laboratory for extreme physics.

4. *Cosmology and Dark Energy* – VLOT will permit a better understanding of the nature of "dark energy", the mysterious component of the Universe responsible for the "anti-gravity" on large scales that is driving the Universe's accelerating expansion. VLOT will allow us to discover and identify distant type Ia supernovae, the "standard candles" through which distances to galaxies can be determined, and which in turn can be used to map out the dynamics of the Universe as a function of its age. This is the key observable needed to probe dark energy.

<sup>11</sup> <http://tmt.org/science-case>, which also contains a link to the Detailed Science Case document (D. Silva et al.)



### *Canadian Participation in a VLOT*

Virtually all industrialized countries (and several developing ones) are seeking to participate in a VLOT project, which will enable discoveries out of the reach of current-generation telescopes. This reinforces the wisdom of the decision by Canadian astronomers to take an early leadership role in the first promising VLOT project (TMT). In fact, given the strengths and focus of Canadian astronomy, participation in a VLOT is probably more critical for us than for many other countries that are engaged in a broader range of activities. Canada's strong track record in optical-infrared ground-based astronomy

makes it an attractive partner for VLOT collaborations, and Canadian participation is actively being sought by both the TMT and E-ELT partnerships.

Experience with Gemini, CFHT, and JCMT has shown rather clearly that Canada's most effective international astronomical facilities are those in which we have a strong voice. A "second-to-none" partnership share is the optimal way to ensure this. For example, in the case of CFHT, Canada's second-to-none share of the telescope allowed us to have a significant voice in the observatory's instrumentation plans, and to implement a strategy of

re-targeting CFHT to operate primarily in a survey mode to maximize its scientific impact. Analysis of the scientific productivity of CFHT relative to all other similar-sized telescopes shows the wisdom of these decisions (\$2.3).

The two choices for Canadian participation in a VLOT are: (i) continued participation in the Thirty Meter Telescope Project [TMT]; or (ii) withdrawing from TMT in order to participate in the European Extremely Large Telescope Project [E-ELT]. Both projects have advantages and disadvantages, although overall they are similar in scope and in scientific capabilities.



Figure 4-2. Design drawing of the TMT structure and mirror. The structure is designed by DSL, Port Coquitlam, BC.  
[copyright TMT Observatory Corporation]

### *The Thirty Meter Telescope (TMT)*

The TMT partnership proposes the construction of a 30m telescope near the summit of Mauna Kea, Hawaii. The partners in the TMT project so far include Canada, the University of California, and the California Institute of Technology, with strong interest expressed by China, India, and Japan. Canadian astronomers have been involved in the TMT partnership almost from its inception. Canadian agencies have invested around \$22M dollars in the project so far, and have made fundamental contributions to the design of the telescope, dome, and to its proposed instruments. Canada is so embedded in the project that the basic nature of TMT's design, and that of its instruments, reflects the desires of the Canadian community in a deep way. The TMT design is mature, and the telescope is ready for construction; in fact, TMT has already commenced pre-construction activities. In the LRP2010 panel's view, TMT is an outstanding opportunity; participation in the project would secure Canada's place as a forefront astronomy nation for decades. *TMT therefore remains the preferred VLOT for Canada.*

TMT was one of two VLOTs considered in the US as part of the Astro2010 process (the other being GMT). In response to Astro2010, the National Science Foundation (NSF) is organizing a process to select which VLOT receives NSF funding, with a decision by the end of 2011. The involvement of NSF is further complicated by the fact that VLOT funding was the third priority for large projects in Astro2010, and hence NSF participation in a VLOT may be delayed until after higher-ranked projects approach completion.

The absence of a firm NSF commitment to TMT at the time of writing, and the consequent effect on the construction

start for TMT, is the main motivation for examining alternatives to the TMT project in this report.

### *The European Extremely Large Telescope (E-ELT)*

There are a number of differences in the designs of TMT and E-ELT:

- The E-ELT is presently envisioned as a 42m telescope, vs. a 30m telescope for TMT.
- The E-ELT will be located on Cerro Armazones in Chile, whereas TMT will be situated on Mauna Kea in Hawaii.
- The E-ELT utilizes a radical new 5 mirror design with adaptive optics incorporated into the telescope, as opposed to TMT's design, which incorporates adaptive optics (where needed) as an integral part of individual focal plane instruments.

Overall, the science goals and capabilities of both telescopes are similar. To a large extent the preferred telescope design depends on the assumed fraction of time spent on extreme adaptive-optics observations. Funding issues aside, TMT is ready for construction; E-ELT is in the final stages of a detailed design review, and is expected to be ready for construction within 12 months or less.

The LRPP and ACURA jointly commissioned a visiting committee to travel to ESO, and assess the feasibility of Canada joining the E-ELT project. The report of the ESO Working Group can be found in Appendix G. Its conclusion is that participating in the E-ELT is attractive in a number of ways beyond simply giving the nation access to telescopes. It would enable Canada to collaborate with a diverse community of scientists, and provide a large pool of instrumentation contracts to bid on over the long term.

On the flip side, participating in the E-ELT would almost certainly mean withdrawal from both Gemini and CFHT as well as from the TMT project; it would also result in a cultural shift in Canadian astronomy, and result in a long-term decrease in the independence of Canada's national astronomy program.

At this point a distinction must be drawn between the "limited partnership" model implied above, in which Canada has a share of the E-ELT but no other ESO facilities, and a "full membership" model, in which Canada becomes a member state of ESO, with full membership privileges. These two modes of gaining access to the E-ELT are considered in the ESO Working Group Report (Appendix G), and also in an earlier confidential ACURA Report<sup>12</sup>. The cost of each over 20 years is nearly identical. Joining ESO has clear advantages in terms of fraction of telescope time, access to all ESO telescopes, and a path to the ESO postdoctoral fellowship program, thus supplementing NSERC grants. ESO membership also gives Canada access to ESO staff positions, and results in expenses paid for observing runs on ESO facilities. Finally, and very important, full ESO membership in principle provides a larger pool of industrial contracts on which to bid, and hence a larger return to Canada for each dollar spent, though the detailed terms would have to be negotiated. Should Canada decide to participate in the E-ELT project, the LRPP recommends that we negotiate full membership in ESO; past contributions to TMT design should in principle be recognized as part of the entrance fee, though this is a topic for negotiation.

Such negotiation would inevitably involve the important issue of how Canadian participation in ALMA would change under ESO. ALMA is a joint ESO-NSF-NOAJ project in which Canadian

<sup>12</sup> "Report of the ACURA Board Working Group on Very Large Optical Telescope (VLOT) Options", Feb 2010.



participation is through NSF via NAPRA. As an ESO member, Canada would participate through ESO instead, and allowance must then be made in the buy-in to ESO for Canada's past contribution to ALMA construction. There is furthermore the issue of whether an ESO physical presence could be established on Canadian soil – for example, the CADC as an ESO data centre, or an ALMA regional centre in Canada. These topics were beyond the scope of the ESO WG, and also lie beyond the scope of this LRP report. They need to be recognized as important but surmountable complications to joining ESO.

## **Recommendations for a VLOT**

The LRPP's highest priority in this area is to continue our participation in the TMT project. However, the LRPP notes that TMT is facing potentially serious delays that could lead to a construction start that conflicts with our need for "timely access to a VLOT". This concern is reflected in the following recommendations:

### **Recommendation 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.*

### **Recommendation 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.*

Meanwhile, discussions with ESO should continue over the next year regarding all issues pertaining to joining the E-ELT project. In the first quarter of 2012, the LRP Implementation Committee should re-examine Canada's options for a VLOT, and in particular whether a 2014 construction start is indeed feasible for TMT.

### **Recommendation 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.*

Should E-ELT construction also be delayed past 2014, then the TMT-E-ELT issue will have to be reconsidered by the LRP Implementation Committee (\$9.4).

## **4.1.2 The Square Kilometre Array (SKA)**

The Square Kilometre Array (SKA) is a next generation radio telescope being planned by an international consortium comprising more than 20 countries around the world. The unprecedented collecting area, frequency coverage and imaging properties of the SKA will completely transform many fields of astronomical research. The name SKA

refers to its collecting aperture, which is equivalent to a square with sides of 1 km. Such a collecting area is about an order of magnitude greater than the largest single aperture radio telescope (Arecibo) and nearly two orders of magnitude greater than the largest interferometric array (the EVLA). Since the SKA is an unfilled array comprising several thousand individual antenna elements, the collecting area would actually be spread out over a region of continental dimensions. Figure 4-3 shows an artist's conception of the central core of the telescope comprising hundreds of dishes, each about 15 metres in diameter. SKA will operate at wavelengths ranging from centimetres to metres, yielding milli-arcsecond resolution at the shortest operating wavelength. The field of view would be several tens of degrees to full sky, depending on wavelength – much higher than current radio telescopes of similar resolution.

The site for the SKA will be either Australia or South Africa, with a final decision on the site to be made in 2012. Through funds raised by these countries together with international partners, two SKA prototype or pathfinder arrays are being constructed, one in Australia (ASKAP) and the other in South Africa (MeerKAT). These telescopes will have collecting apertures of about one percent that of the SKA, and cost about \$100M each. Though Canada is not a formal partner in these prototypes, Canadian scientists are participating in the design and development of these telescopes, and in the plans to use these telescopes for scientific research.

### **Science with the SKA**

As noted earlier, the SKA has about one hundred times the collecting aperture of the largest existing interferometric radio telescopes, and correspondingly higher sensitivity; furthermore, because of its large dimensions it will have resolution





Figure 4-3. An artist's conception of the distribution of antenna elements in the inner core of the SKA, where the antennas are closely spaced. The outer antennas would be distributed over an area of continental dimensions to provide exceedingly high angular resolution. [SKA Project Development Office and Swinburne Astronomy Productions]

comparable to that of VLBI arrays, but with much higher image fidelity. Figure 4-4 shows a simulation of the appearance at the neutral hydrogen wavelength of 21 cm of the Universe of normal and active galaxies as seen by the SKA, complemented by the simulated appearance at CO mm and sub-mm wavelengths with ALMA.

The enormous sensitivity of the SKA will permit us to contribute to answering many of today's most pressing astrophysical questions. The following are examples of some of these questions and how they will be addressed by the SKA:

*1. What is the nature of Dark Energy?*

The SKA will be able to detect neutral hydrogen in galaxies to redshifts greater than one (lookback times of order two-thirds of the age of the Universe). One application of these data will be to detect early density fluctuations in the Universe, which serve as a tracer of the early expansion of the Universe, and constrain the equation of state of dark energy.

*2. Was Einstein right about the nature of gravity?* The SKA will discover and make

sensitive high-precision timing observations of many new millisecond pulsars. This will allow new tests of Einstein's theory of general relativity, constraints on the equation of state of dense matter, as well as the construction of an ultra-sensitive Pulsar Timing Array for the detection of nanohertz gravitational waves.

*3. How do galaxies and their stars form, and when did this formation begin?* The ionizing ultra-violet radiation from the first stars and galaxies, and of the first large-scale structure formation, will be obtained by imaging neutral hydrogen and tracking the transition of the intergalactic medium from a neutral to ionized state.

*4. How do earth-like planets form, and can we detect life in the Universe?* With its sensitivity and resolution, the SKA will be able to probe the planetary formation process. The direct detection of transmissions from another civilization would provide immediate and direct evidence of life elsewhere in the Universe, and the SKA will provide sufficient sensitivity to enable, for the first time, searches for unintentional emissions or "leakage".

The most far-reaching advances will require these questions to be explored in a complementary way at several wavebands, requiring access also to next generation telescopes in the optical, infrared and sub-millimetre wavelengths. Fortunately, Canada will have access not only to the SKA but also to several complementary facilities (e.g. ALMA, JWST and a VLOT) and thus is well-poised to exploit the full scientific potential of the SKA.

### SKA development

The SKA is currently in the design phase funded by the international consortium partners. The international effort is centred in Europe and receives funding there through the Seventh Framework programme (FP7), under the auspices of the European Strategy Forum on Research Initiatives (ESFRI). The program is termed the Preparatory Phase Project for the SKA (PrepSKA). Non-European countries obtain their own design funding to contribute to the international effort. Canadian participation is currently at the

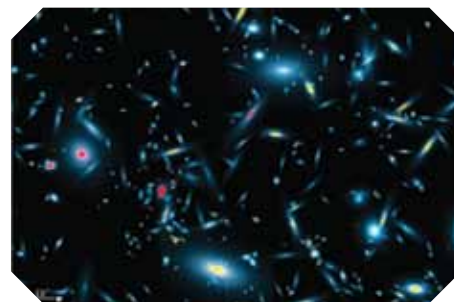


Figure 4-4. A simulation of the sky seen by the SKA in the 21 cm line of neutral hydrogen (blue) and line emission as would be seen by ALMA in the mm and sub-mm lines from the CO molecule, both traced to a redshift of  $z = 1$ . The CO J=1-0 line is shown as yellow and the CO J=6-5 line as red. Such data will be used to trace galaxy evolution, and the galaxies seen with the SKA will also be used for other cosmological observations. [D. Obreschkow, U. Oxford and SKA Design Study].

\$8M level (2008-2012) from a variety of sources, including NRC, NSERC, and CANARIE. The plan calls for prepSKA to end in 2012, followed by a detailed design phase or preconstruction phase. Construction is then scheduled to proceed in three phases. Phase 1 (construction of 10% of the full array at low- and mid-band frequencies<sup>13</sup>, and first science) will run for approximately 4 years, and Phase 2 (completion and commissioning at low- to mid-frequencies) will last for 6 years. A third phase will follow which will allow the SKA to operate at high frequencies. The timing of these construction phases is uncertain: Phase 1 is currently proposed for a 2016 start, but, as noted below, we view this as optimistic.

The full cost for Phases 1 and 2 of the SKA is estimated at €1.5Billion, with €350Million targeted for Phase 1 construction and the remaining €1.2Billion targeted for Phase 2. The international partnership shares are equally divided between the U.S., Europe, and other partners. Canada's share would be about ten percent, which corresponds to its current share of the design activity. At this level the costs for Canada beyond 2012 to the end of Phase 2, in Canadian dollars, are estimated to be:

|  |        |
|--|--------|
| Detailed design and engineering (pre-construction phase) | \$15M  |
| SKA Phase 1 construction (4 years)                       | \$56M  |
| SKA Phase 2 construction (6 years)                       | \$154M |

(Note that the stated funding levels for phase 1 and 2 construction are targets based on conceptual designs, and will be updated during the pre-construction phase.)

Canada was one of the founding members of the SKA consortium and is currently a vital part of the international design team under prepSKA. Canada co-leads the Antenna Design work package with the US Technology Development Program, which will design a prototype SKA Dish Verification Antenna to be tested at the VLA site. Canada also leads the Correlator and Central Beam-former work package within the Digital Signal Processing program. This builds on the experience already gained in the design and construction of composite materials antennas and the development and delivery of the EVLA correlator. Figure 4-5 shows a prototype antenna developed by HIA at DRAO, and an artist's rendering of an SKA antenna element with an offset feed configuration being designed at DRAO.

### *Technical challenges and opportunities for Canadian industry*

The data flow rate in the SKA will be much larger than the total current data rate circulating around the globe, presenting an extremely challenging problem with very high impact in the ICT sector. The SKA is the single largest technical challenge ever faced in astronomy; it is exceptionally dependent upon technological innovation in signal processing and circuit design. Given the wide applicability of these techniques in ICT, the technologies developed for the SKA will almost certainly find applications elsewhere. For example, the low noise amplifiers and analog-to-digital converters will impact phone, radar and wireless communications technologies and Canadian companies (Breconridge, IBM Canada) are already participating in these developments. Dish manufacturing techniques must be improved to meet new price-performance limits and new composite technologies are already being investigated. Yet further innovation



Figure 4-5. (Left) The 10-m Mark 2 prototype composite antenna reflector system at the HIA Dominion Radio Astrophysical Observatory. The reflector has a 0.5mm surface accuracy. The Phased Array Feed Demonstrator, or beam-former feed, is mounted at the prime focus. [NRC-HIA] (Right) A rendition of the latest composite offset reflector designs being developed at NRC-HIA. [NRC-HIA]

will be needed in the algorithms used to process the data feeds. Overall, the SKA presents an outstanding opportunity for industrial involvement that will multiply the economic return to Canada from its investment in this project.

The LRP2000 report recommended that Canada position itself to be a partner in the SKA. The MTR in 2005 further supported Canada's participation in the SKA, and recommended that funding for the design of the SKA be the highest priority for engineering design work to prepare Canada to become a leading partner. The follow up by NRC-HIA and other team players on these recommendations have today placed Canada in a position to take one of the leads in antenna design and signal processing. It is vital to maintain this momentum by fully engaging in the SKA effort in this decade as the detailed design phase proceeds toward Phase 1 construction.

We anticipate that SKA will be the next high-priority Very Large Facility in

13 The low frequency band is approximately 70-450 MHz, and the mid frequency band 450 MHz-10 GHz; the high frequency band is up to 25 GHz or higher.

Canadian astronomy. (A discussion of the timing of the SKA project relative to a VLOT is considered in §9.1.) The LRPP makes the following recommendation:

### Recommendation 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.*

## 4.2 Medium- and Small-Scale Projects

The importance of flexibility in dealing with priorities for medium- and small-scale projects cannot be overstated (see §9.4). Some of these projects arise and can be constructed on timescales shorter than the LRP horizon, and funding opportunities (e.g. CFI) are more flexible than those for larger projects. The following is a discussion of projects of great interest at the date of writing of this plan. It should not be considered to be in any sense restrictive of future opportunities. (We note that one medium-scale project, CFHT new instrumentation, has already been discussed in §3.1.1. We further note that ngCFHT, which could fall in the medium-large category depending on Canada's eventual share of the telescope, is initially recommended for R&D, which falls in the small-scale category.)

We start our discussion with CHIME, which, in the view of the LRPP, is timely, has strongly focused scientific objectives with exceptionally high merit, and which could have an important impact on the understanding of Dark Energy, one of the leading cosmological puzzles in this era.

### 4.2.1 CHIME

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a proposed 21-cm experiment for mapping the cosmological neutral hydrogen distribution in order to measure the evolution

of large-scale correlations of structure in the Universe through cosmic time. This would help determine the nature of dark energy, a phenomenon discussed elsewhere (§2.1) in this report. CHIME would also be a useful instrument for pulsar astronomy.

In its currently proposed form, CHIME would operate in the radio frequency range of 425 to 850 MHz and would consist of five fixed cylindrical parabolic reflectors oriented North-South, populated with low-noise room temperature receivers along the focal line. The signals from adjacent cylinders are combined to form the instantaneous beam; the instrument surveys half the sky every day, as the Earth turns. The full CHIME instrument would be 100 m on a side, and has been estimated to cost about \$15M. The cost is relatively low because the telescope has no moving parts. Construction could in principle begin quickly as no components require technology development.

HIA-DRAO (Penticton, BC) has been suggested as an excellent site for CHIME, given its status as a radio-quiet zone. DRAO possesses world-class expertise in low frequency astronomy and a mandate to provide observatory facilities for astronomical research (§3.3.3).

The LRPP notes a significant groundswell of support for CHIME, as evidenced at Town Hall meetings, with the possibility of high-impact science being done in Canada, by Canadians. The LRPP also notes that, together with the EVLA and ALMA (§3.1.5 and 3.1.3), CHIME has the potential to help strengthen and broaden the Canadian radio astronomy community. This would be valuable as preparation for the SKA, both technically and scientifically. Not yet having been rigorously peer-reviewed, the actual science capabilities, technical feasibility, and realistic cost of CHIME are not fully known at this

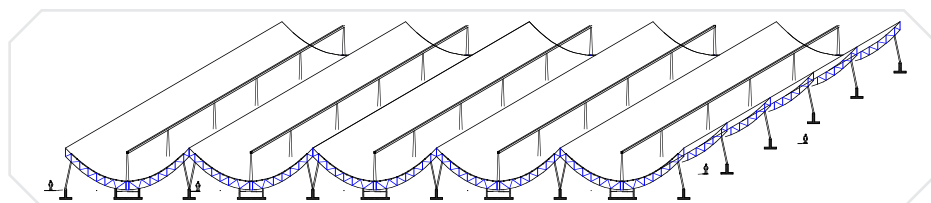


Figure 4-6. Artist's impression of the CHIME collecting surface, covering approximately 100m x 100m. [CHIME Collaboration/Mark Halpern]



time. In any event a rigorous technical and scientific review involving all these aspects is beyond the scope of this report.

We note, however, NRC's track record of collaboration with universities, and in particular DRAO's assistance with the CHIME project to date through allocation of space, effort and hardware for CHIME prototype tests. We encourage the continuation of this support; projects like CHIME provide a valuable means of sharing NRC expertise in radio astronomy with the broader community.

## Recommendation 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.*

Finally we note that CHIME highlights some of the inadequacies of funding mechanisms for Canadian science. This is discussed further below (§6.4.2 [CFI]).

### 4.2.2 CCAT

The Cerro Chajnantor Atacama Telescope (CCAT) is a 25m sub-mm telescope proposed for one of the highest and driest sites in the world: the Atacama plateau in Chile, slightly above the ALMA site. CCAT will address a wide range of fundamental scientific programs, including the study of the early Universe, galaxy evolution and the formation/evolution of stars and planetary systems. CCAT will operate at the same wavelengths

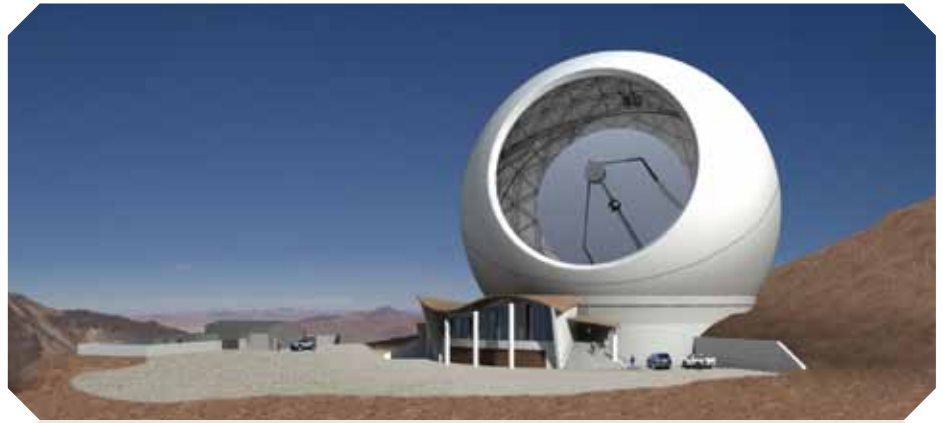


Figure 4-7. An Artist's impression of the CCAT telescope on Cerro Chajnantor, Chile. [CCAT Consortium]

(0.3-1.4 mm) as ALMA; however, CCAT possesses a much wider field of view, making it ideal for survey work. This is in contrast to ALMA, which is to be used for high-spatial resolution observations of individual targets. At relatively long wavelengths ( $>700\ \mu\text{m}$ ), CCAT will be an order of magnitude more sensitive in the continuum than ALMA. Clearly CCAT will be a very powerful sub-mm observatory working in close synergy with ALMA.

The CCAT project is led by a consortium of US institutions (CalTech, JPL, Cornell, U. of Colorado) with international interest in participation by the UK and Canada. The project cost, development and construction included, is estimated by the US Consortium at \$US140M, with operations starting as early as 2017, but perhaps more realistically 2020 according to Astro2010. There is considerable interest within the far-IR/sub-mm Canadian community in joining CCAT; potential Canadian contributions include instruments, antenna design, and the dome structure. (The current dome design is largely inspired by that for TMT, which was designed by Canadian industry.)

The LRP2010 recognizes the scientific benefits of CCAT and the importance of this major international facility for the health of the far-IR/sub-mm Canadian community, especially towards the end of this decade and beyond.

## Recommendation 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).*

A decision to commit construction and operation funds should be considered when the project has passed all of its technical reviews; this decision will take into account CCAT's priority rating (\$9), and should be conditional on what agreement and partnership is offered. Given the current state and likely evolution of this project and other LRP projects, this will probably occur near the middle of this decade, in time for a possible mid-term LRP review.

### 4.2.3 Astronomy in the High Arctic

Demonstrating and maintaining Canadian sovereignty over its Arctic territory has become an important national priority. One method of accomplishing this goal is through Arctic research programs; a major initiative is now underway to exploit the Canadian High Arctic for astronomical observations.

The Earth's polar regions offer significant advantages for ground-based optical and infrared astronomy. These include cold, dry conditions, long periods of darkness, and the potential for unsurpassed image quality. Observations from the Antarctic glacial plateau indicate that there is relatively little high-altitude turbulence: if one could build a telescope at an altitude 200 m above the Antarctic plateau, the seeing would be unsurpassed by any except orbiting space telescopes. However,

strong low altitude turbulence means that it would be difficult or impossible to exploit this superb image quality for astronomical observations.

The exciting results from Antarctica have motivated a Canadian team to look towards the opposite pole of the Earth. The Canadian Arctic develops a strong winter polar vortex, within which stable conditions are expected. Moreover, many high, isolated peaks are near the seacoast, avoiding the conditions responsible for the strong surface-layer turbulence blanketing the central Antarctic icecap. An additional advantage of the High Arctic is accessibility. Major permanent bases (Alert and Eureka) are accessible by air year-round. Both are military outposts with manned weather stations served from southern Canada by large cargo planes. Eureka is supplied annually by ship.

Three years ago, a Canadian team led by scientists at Canadian universities and at HIA began a program of *in situ* testing of mountain sites in Northern Ellesmere Island (latitudes 80-83 deg N), with the specific aim of characterizing the ground-layer seeing. On a 600m-high ridge 15 km from Eureka, a consortium of Canadian universities and government agencies operates the Polar Environment Atmospheric Research Laboratory (PEARL) – the most northerly permanent manned research station in the world. In the summer of 2009, the team deployed equipment designed to measure ground-layer turbulence at the PEARL site. Early results from the spring 2010 campaign are extremely encouraging: they show a site with minimal ground-layer turbulence (and the expectation of excellent free atmosphere seeing, as experienced above Antarctica Dome C). If these observations are confirmed, then Canada possesses possibly the best ground-based sites on the planet for astronomical optical and near-infrared observing.

Further observations must be made to fully characterize the Ellesmere Island site before one can draw firm conclusions from these preliminary results. We urge that this site testing be continued and completed at PEARL, and that additional site testing be conducted at other mountain sites on Ellesmere Island.

It is important to remind the reader of the impact of seeing on astronomical imaging. A 3 metre telescope with 0.3 arcsec seeing is approximately equivalent in figure of merit (for point source detection) to an 8 metre in 0.8 arcsec seeing. Thus a relatively small telescope (say 2-4 metre aperture) in the High Arctic would be equivalent to the Large Synoptic Survey Telescope (LSST, 8m aperture, 0.8 arcsec seeing) being constructed in Chile as the #1 priority for large ground-based OIR facilities (from Astro2010).



Figure 4-8. Mountains at the northern end of Ellesmere Island, latitude 80N. These mountains rise to a maximum height of 2700 metres, and are the highest mountains in eastern North America. [NRC-HIA]



Figure 4-9. (Left) the PEARL research station, 15 km from Eureka on Ellesmere Island. [CANDAC/James Drummond] (Right) Satellite imagery of northern Ellesmere Island. Red crosses represent sites which are being considered for site testing. The blue cross is Barbeau Peak (altitude 2616 m), the highest point in eastern North America. [Eric Steinbring]

All of the science drivers for an LSST would be valid for a small Arctic telescope; one could furthermore imagine many international groups having an interest in participating in facilities at a uniquely Canadian Arctic site. Therefore, should the PEARL results, and further testing, confirm the quality of the Arctic sites, then Canada should proceed with a science case, design studies, and construction of a moderate aperture (1-4 metre) wide-field imaging telescope at the site. The LRP Implementation Committee should keep a close watch on the development of the Ellesmere site testing program.

### Recommendation 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.*

### 4.2.4 Next Generation CFHT

The science case for a Next Generation CFHT (ngCFHT), which we define here as an 8-15 metre-class telescope equipped with a wide-field multi-object spectrograph (WF MOS), is universally recognized, having been thoroughly explored in several studies during the past decade<sup>14</sup>. Indeed, it is worth noting that, a decade ago, the LRP2000 report stated that:

*“The LRPP recommends that our community quickly obtain significant participation ... in the construction and operation of a new, optical/infrared 8 metre class telescope. Wide-field capability (WF8m) should be given priority.”*

Since that time, the science case for such a facility has only sharpened, with an appreciation of how it could enable excellent science, most notably by: (1) constraining the dark energy equation of state to a level of a few percent and; (2) exploring the structure, kinematics and chemical evolution of the Milky Way (i.e., Galactic archaeology). A 10m telescope equipped with an WF MOS-like instrument would also have a transformative impact in a wide range of fields, including stellar structure and evolution, large-scale structure, galaxy formation and evolution, dark matter, AGN physics, and the epoch of reionization. Furthermore, ngCFHT+WF MOS would be a unique resource for follow-up spectroscopy, both for the European Gaia satellite mission,

14 See the LRP White Paper by Côté et al.: <http://casca.ca/lrp2010/Docs/LRPReports/ngcfht.pdf>



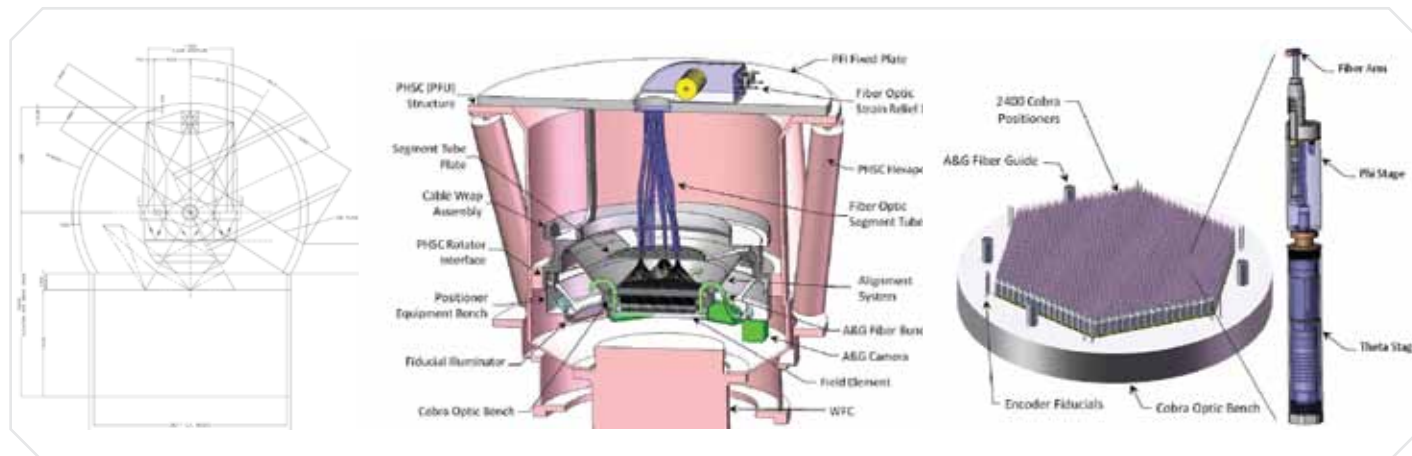


Figure 4-10. (Left) Cross sectional view of the CFHT with a 10m telescope mounted on the existing pier. [Dynamic Structures Limited] (Middle) Schematic of the WFMOS Prime Focus Instrument (consisting of the acquisition and guide cameras, the field element, the positioner subsystem and other telescope-mounted components) taken from Ellis et al. (2009). [JPL/CalTech] (Right) The Cobra positioner system from Ellis et al. (2009), which covers the WFMOS focal plane with 2400 positioners to fill a hexagonal field. A magnified view of a single positioner is shown at the right. [JPL/CalTech]

and also for LSST and Euclid/WFIRST, two of the highest priority projects recommended by Astro2010, and for CST. (The nearest analogue in terms of potential impact across subfields is the Sloan Digital Sky Survey [SDSS], with more than 3000 papers, covering nearly every field in astrophysics, and with 100,000 citations to date.)

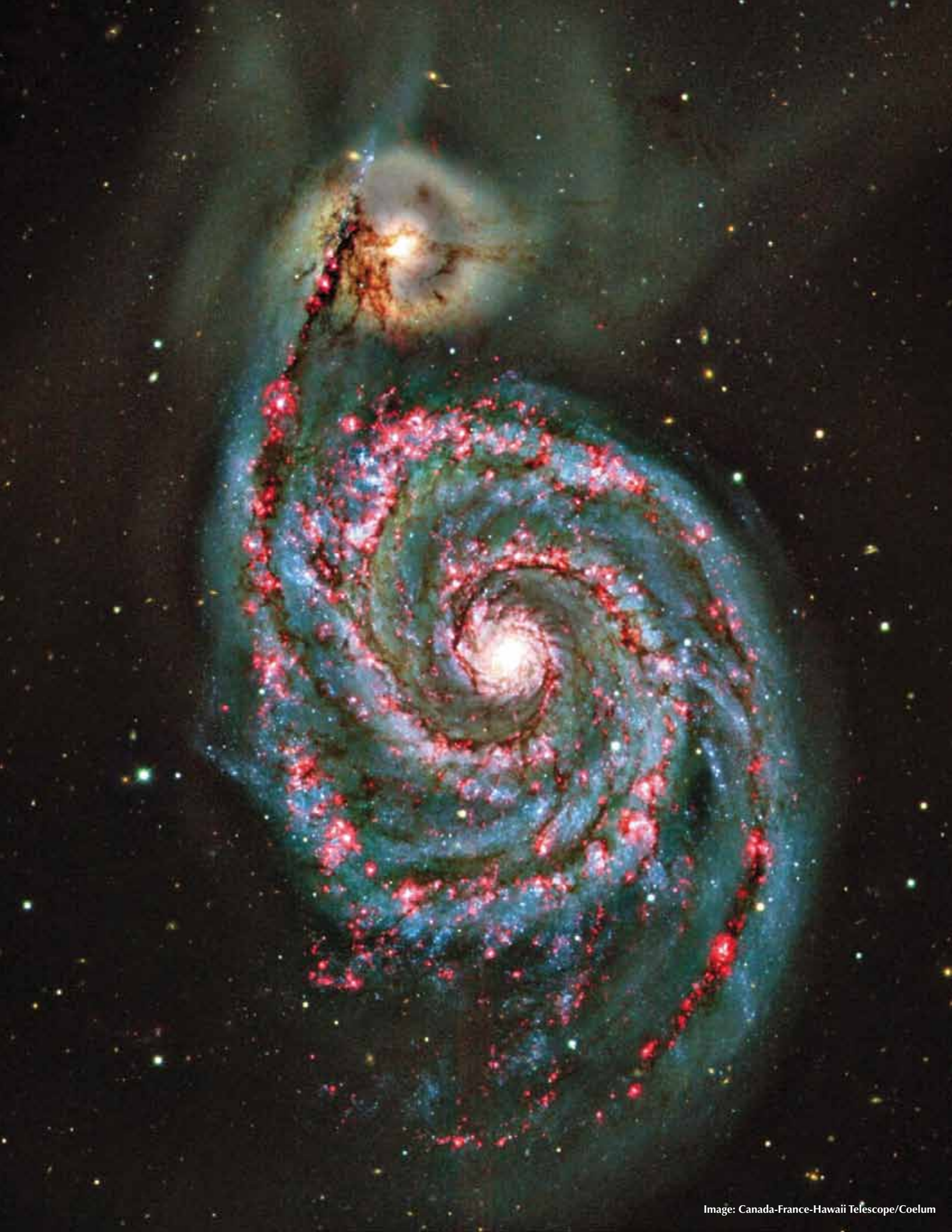
While the science case for an ngCFHT is unassailable, there are some strategic issues. First and foremost is cost: although no detailed design study exists, it is expected, scaling from existing telescopes, that an ngCFHT+WFMOS would cost of order \$200M, or \$50M for a 25% share. Although this could be reduced somewhat by the value of the CFHT site and infrastructure, it would nevertheless be difficult or impossible to fund such a share (not to mention find the human resources to work on the project) if we proceed with our number one ground-based optical priority, a significant share of a VLOT telescope. The second issue

is timing: it is stated that, to have maximal impact in its science areas, ngCFHT should achieve first light around 2020. This means a construction start in 2015, which would conflict with the start of operations of the next generation CFHT instruments, although such an early construction start seems very optimistic given the present state of the project. Third, there is a proposal to develop a related (albeit less powerful) capability on Subaru (the PFS instrument); if PFS is funded, Canada could gain access to a small amount of time through its Gemini membership. Finally there is the issue of the evolution of our collaboration with France in an ngCFHT project.

In short, ngCFHT is a scientifically interesting concept, but neither the scope (including aperture), cost or schedule of the ngCFHT are well determined, so it is important to establish better estimates for these before the project can proceed further.

## Recommendation 20

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







*The investments in infrastructure, training  
and industrial capacity in space- and  
balloon-based astronomy made  
over the last decade have made  
Canada a significant player  
in the world space  
astronomy  
theatre.*



## 5. New Space Facilities

The investments in infrastructure, training and industrial capacity in space- and balloon-based astronomy made over the last decade (§6.4.3) have made Canada a significant player in the world space astronomy theatre. We have built capacity in our aerospace industry, as well as in our universities, with important academic/industrial ties forming in the process. Indeed, for the first time, Canada is now capable of leading a space astronomy mission equivalent to NASA explorer-class missions.

Space astronomy is, however, at a crossroads. Many of the most important science questions require large-scale facilities to make progress. High-impact space astronomy is thus becoming increasingly expensive and most planned missions now require international collaboration. Careful thought and planning are required to determine what fraction of Canada's resources should be spent on Canadian-led initiatives (which would generally be smaller scale projects that would tackle interesting but highly targeted science questions). Such initiatives are in contrast to grander internationally-led projects that have the potential to answer major science questions, and that would involve a larger fraction of the Canadian community.

To help tackle these challenging issues, as well as form a basis for its 2010 Long-Term Space Plan (LTSP) exercise (still under review), CSA sponsored five "Discipline Working Groups" (DWGs) in astronomy, to inform itself about the ambitions of Canadian researchers engaged in space astronomy. These DWGs were comprised both of university-based and HIA-based researchers, and representatives of industry; they discussed the following areas:

- High energy astrophysics
- Far infrared astronomy

- Cosmic microwave background
- Space-based wide-field Ultraviolet-optical-near-infrared
- UV astronomy, imaging and spectroscopy

LRP recommendations have been made partially on the basis of these DWG reports, along with LRP white papers, and Town Hall discussions, but without knowledge of the content of the LTSP. The reader is referred to §6.4.3 for a further discussion of the Canadian Space Agency and its role in Canadian astronomy.

An important consideration is that the CSA needs to respond rapidly to emerging opportunities, which often evolve on short timescales. Recommendation 25 addresses this point in the context of High Energy astrophysics, but it is equally applicable to all other domains of space astronomy.

A major issue facing CSA, and space astronomy in particular, is that both are underfunded in Canada by a factor of about 5 relative to NASA in the US (after normalization by population). To ensure Canadian global competitiveness in space astronomy, and to participate in the missions that we are recommending (§9.2), space astronomy needs a continuing budget at least that of recent years, during which time the space astronomy yearly expenditures have been greatly enhanced due to the construction phase of JWST. This is an urgent structural issue that faces space astronomy, and in fact all of space science.

A further issue for the LRPP is that it is not possible at the present time to provide cost estimates for Canada for many of the proposed missions in this section. This leads to the following recommendation:

### **Recommendation 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.*

Finally we note the discussion of university-based instrumentation laboratories in §3.2.2; these laboratories are a key to the development of instrumentation and new technologies for space missions.

## 5.1 Dark Energy

In the wake of Edwin Hubble's discovery of an expanding Universe, most astrophysicists favoured models in which the overall expansion would be dominated by the matter density of the Universe, and thus slowing down with time. Thus it came as an immense surprise when in 1998 two teams independently discovered, through observations of faint, distant supernovae, that the Universal expansion is accelerating rather than decelerating. The source of the accelerated expansion is somewhat whimsically termed "dark energy"; although dark energy dominates the dynamics of the expansion of the Universe, virtually nothing is known about it. The discovery of dark energy is perhaps one of the most unexpected and exciting results in all of physics in the past century.

We are approaching the limits of what can be discovered about dark energy (DE) from ground-based observations. We know that DE behaves much like

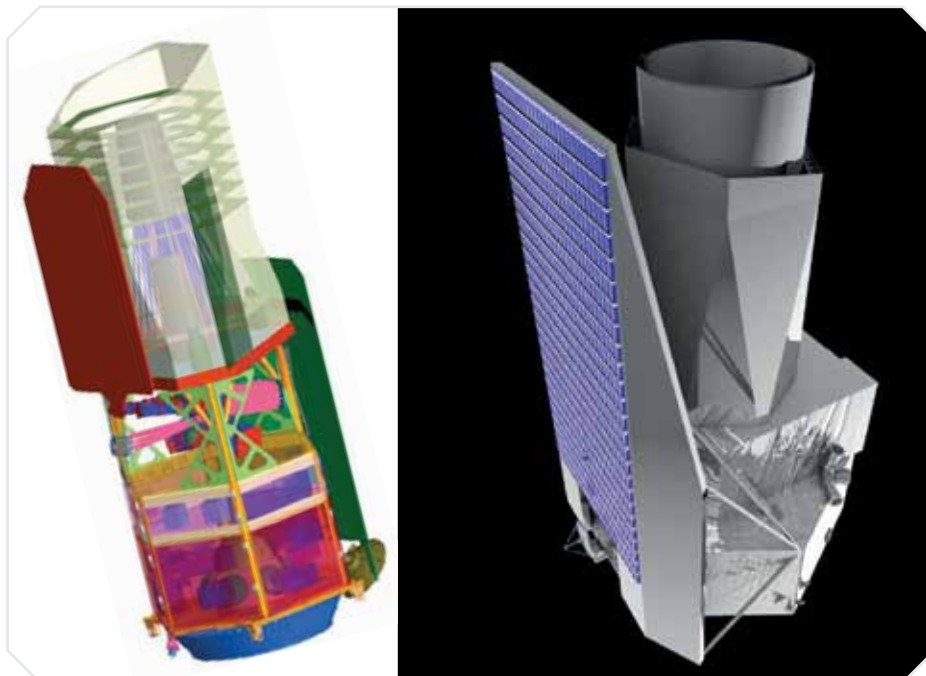


Figure 5-1. (Left) Artist's impression of NASA's WFIRST infrared satellite. [NASA/JPL-CalTech] (Right) Artist's impression of ESA's Euclid satellite mission. [ESA]

a “cosmological constant” of the form hypothesized by Einstein, but we still lack any understanding of how DE evolves with cosmological time – a critical diagnostic when trying to connect DE with theoretical physics. The next step in the remarkable story of Dark Energy research is widely recognized to be observations from space; such observations avoid calibration problems which limit our ground-based work, and will allow not only the detection of supernovae at high redshifts, but also weak lensing as a function of redshift. Canadian (and French) astronomers lead the world in this field through their participation in the CFHT dark energy experiment SNLS, which has constrained the nature of dark energy better than any previous survey (see §2.2).

Both the US Astro2010 process and ESA have identified Dark Energy satellite missions as the number one priority

for space astronomy. Participation in the ESA Euclid or NASA/DOE WFIRST missions (which are both equipped for near-infrared observations) is an important next step for Canadian astronomy. Euclid has the advantage of better angular resolution in the visible than the current WFIRST concept. In a recent development NASA appears to be moving towards immediate participation in Euclid as its highest priority in this science area, though this does not exclude a future WFIRST mission with different capabilities and objectives than Euclid.

Given the scientific importance of the dark energy question, and Canada's track record of ground-based scientific discoveries in this area, it is essential that Canada participate as a *significant* partner in one of the dark energy satellite missions due for construction this decade. This would advance and extend

our trajectory of JWST involvement into the coming decade. In the following recommendation we leave open the question of which mission is to be joined.

Possible instrumentation contributions to Euclid/WFIRST include an optical channel to the telescope, and/or the fine guidance system. These and other options are actively being investigated at the present time.

Further work is needed to assess whether complementary ground-based observations with Canadian telescope time could improve the science case and lever Canadian participation, and how important other science drivers for each satellite are for the Canadian community. If participation in WFIRST or Euclid is not possible, then the LRPP recommends exploring the possibility of a Canadian-led imaging satellite, CST (Canadian Space Telescope), possibly with other partners, and focusing on UV-visible wavelengths, as a complement to WFIRST/Euclid.

## Recommendation 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.*

## 5.2 High Energy Astrophysics

High Energy Astrophysics (HEA), usually meaning X-ray and  $\gamma$ -ray astronomy, encompasses an extremely wide range of the astrophysical sciences, including a broad range of scales, both temporal and spatial. HEA sources include stars, black holes, neutron stars, white dwarfs, supernova remnants, the interstellar medium, galaxies, active galactic nuclei, galaxy clusters, and gamma-ray bursters, all emitting via fundamental but extreme physical processes, including extremes of gravity, density, temperature and magnetic field. HEA observations are highly complementary to observations at other wavelengths, sampling completely different physical regimes, often in the same object. On the other hand, many HEA phenomena are inaccessible at any other waveband, and observations in the X-ray regime and in most of the  $\gamma$ -ray regime can be performed only from space.

There is considerable Canadian expertise and activity in many of these areas, notably neutron stars, white dwarfs, supernova remnants,

active galactic nuclei and galaxy clusters, with most expertise in the domain of X-ray astronomy.

HEA over the past decade has been the fastest growing subfield of astronomy in Canada. At least 17 astrophysics faculty hirings have been made since 2000 in HEA and related fields, including five Canada Research Chairs. This represents an approximately five-fold increase over the number of Canadian HEA faculty in 2000. Considering the cadre of postdoctoral, graduate and undergraduate student researchers these faculty employ, the HEA community in Canada now includes approximately 90 people. Thus the community is young, active and growing. While LRP2000 made virtually no mention of X-rays or  $\gamma$ -rays, MTR2005 specifically noted the growth of Canadian HEA, identifying its potential “to lead the way to a new area of exciting space astronomy in Canada”.

The LRPP asserts that significant Canadian involvement in one or more forefront HEA missions is essential for nurturing and retaining the vibrant expertise and talent of the Canadian HEA community.

The LRPP notes in this regard Canada’s involvement in Astrosat, an Indian-led mission that will carry several X-ray instruments, in addition to the Canadian CSA-funded contributions to the UV instrument UVIT. Astrosat’s instrument complement is interesting as it will allow very broad, simultaneous energy coverage of a wide variety of sources. As such it will be of significant use to a portion of the Canadian HEA community.

The LRPP applauds recent CSA initiatives toward further encouraging HEA in Canada, specifically the funding of a Discipline Working Group (DWG) from 2007 to 2009 to define top priorities for the field and identify missions in which the CSA should consider involvement.

Moreover, the LRPP is pleased that the CSA has worked expeditiously to embark on the JAXA Astro-H mission, with a contribution of a metrology system, addressing the HEA DWG’s top short-term priority. The HEA DWG noted not only that Astro-H science was an excellent match to the expertise of the Canadian community, but also that given its long 12-m focal length (required for its focusing high-energy X-ray optics), a metrology system would be required. Space metrology is an area in which Canadian industry has expertise. Following delivery of the HEA DWG report, CSA supported and completed concept studies for a metrology system. A competitive process will select a contractor for supplying the instrument. This has the potential to lead Canada not just toward involvement in a world-class HEA facility, but in addition to be a stepping-stone toward future space-metrology contributions. The LRPP thus strongly supports the CSA’s efforts toward Canadian involvement in Astro-H, and encourages the CSA to adequately fund this effort, especially given the

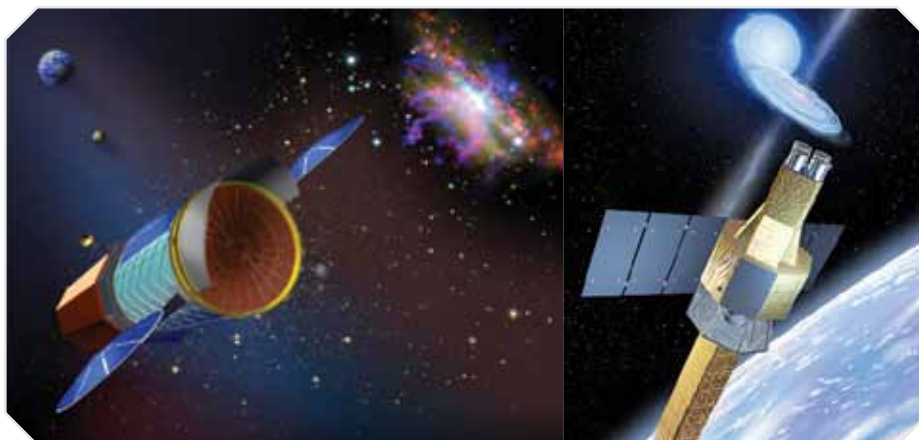


Figure 5-2. (Left) IXO satellite. [ESA/NASA] (Right) Astro-H satellite. [JAXA/A. Bamba]



promise of this technology to secure other future opportunities.

### **Recommendation 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.*

Specifically, there are many very interesting mission concepts being considered that would require metrology systems; these include the European SIM-BOL-X hard X-ray mission (which may be proposed for the next ESA Cosmic Vision competition) as well as ambitious focusing gamma-ray telescope concepts such as DUAL. In the near term the ESA PROBA-3 mission will rely upon formation flying to create an occulter-based solar coronagraph. Longer term, formation flying techniques underlie some of the most ambitious optical interferometry missions such as the Terrestrial Planet Finder (TPF) and ESA's Darwin.

The HEA DWG's top long-term priority is for Canadian involvement in the joint European/U.S./Japanese mission International X-ray Observatory (IXO). IXO will be a 0.1–10 keV high-throughput telescope having effective area greater than 10 times that of XMM-Newton, currently the largest-area focusing X-ray telescope. IXO will have excellent ( $R$  greater than 1000) spectral resolution with good (less than 5 arcsec) angular resolution and excellent (less than 1 millisecond) time resolution. These properties make IXO an excellent match for the broad range of HEA science encompassed by the large, young and active HEA community in Canada. Specifically, IXO's sensitivity and spectral resolution will make it a workhorse for studying, among

other topics: AGN and, for example, relativistically-broadened iron lines – telltale diagnostics of black-hole spin; the outflows of galaxies in clusters, and their impact on the intracluster medium; and the equation-of-state of dense matter via spectroscopy of both accreting and non-accreting neutron stars,

IXO will also require a long focal length, hence a dedicated metrology system. Very recently, the U.S. Decadal Survey Astro2010 ranked IXO the top priority for X-ray astronomy, and 4th among large-scale space-based initiatives. Although Astro2010 found IXO technologies to be “too immature at present for accurate cost and risk assessment,” they nonetheless believe IXO is likely to be ready for mission start at the beginning of the next decade. Even so, for a mission of this scope and complexity, Canadian involvement in this technology development work should be initiated as soon as possible, with an eye toward metrology as one possible contribution.

### **Recommendation 24**

*The LRPP strongly recommends Canadian R&D involvement in IXO as its number 1 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.*

While this recommendation emphasizes metrology, other aspects of the mission may also be a match to Canadian capabilities (e.g. design, software and data analysis).

More broadly, however, the LRPP notes a need for Canada to respond rapidly to opportunities, particularly in HEA, but also in other areas of space astrophysics. The Canadian HEA community currently consists of relatively young astrophysicists whose primary expertise is scientific, rather than HEA technology development (with the exception of the McGill ground-based  $\gamma$ -ray group). There is potential to develop the expertise required to design, build and lead a forefront HEA space mission in Canada in the coming decades. Involvement in external initiatives both to further HEA science goals, as well as to develop Canadian HEA technological foundations, is required for this, however.

### **Recommendation 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.*

Finally we again note the broad applicability of this recommendation to all areas of space astronomy.

### 5.3 Far IR

A typical star-forming galaxy emits the majority of its total energy output at far-infrared wavelengths, and this is a crucial window for investigating a host of phenomena, spanning the full range of scales from large to small, including dust emission in galaxies, star forming complexes and proto-planetary systems. The far infrared (FIR) spectral region covers the wavelengths between  $\sim 20 \mu\text{m}$  and  $\sim 200 \mu\text{m}$ .

Since the Earth's atmosphere is opaque to FIR wavelengths, balloon-based and/or space-based payloads are required to study astrophysical phenomena at these wavelengths. Most of our knowledge of the FIR Universe comes from a few space missions: the NASA-led IRAS mission launched in 1983; ISO, led by ESA, in 1995; and the very successful NASA-led Spitzer mission in 2003. The current premier FIR facility is Herschel, a 3.5m space telescope developed by ESA and successfully inserted into the second Lagrange point in 2009 for a three-year mission. As discussed in §3.2.2, Canada is actively involved in Herschel through hardware and software contributions for two out of the three science instruments onboard the spacecraft. Herschel's operation is now well underway and the mission is poised to be a major success.

The main opportunity for Canadians, late in this decade if not beyond, is SPICA, a Japanese-led mission with possible participation from ESA and Canada. CSA is investigating a role for Canadian participation in the mission that leverages our expertise in Fourier Transform Spectroscopy (FTS) technology. SPICA will be 100 times more sensitive than Herschel, by virtue of the fact that it has a cooled primary mirror. Ambitious FIR interferometer space projects (e.g. SPIRIT and FIRI) are under development worldwide but

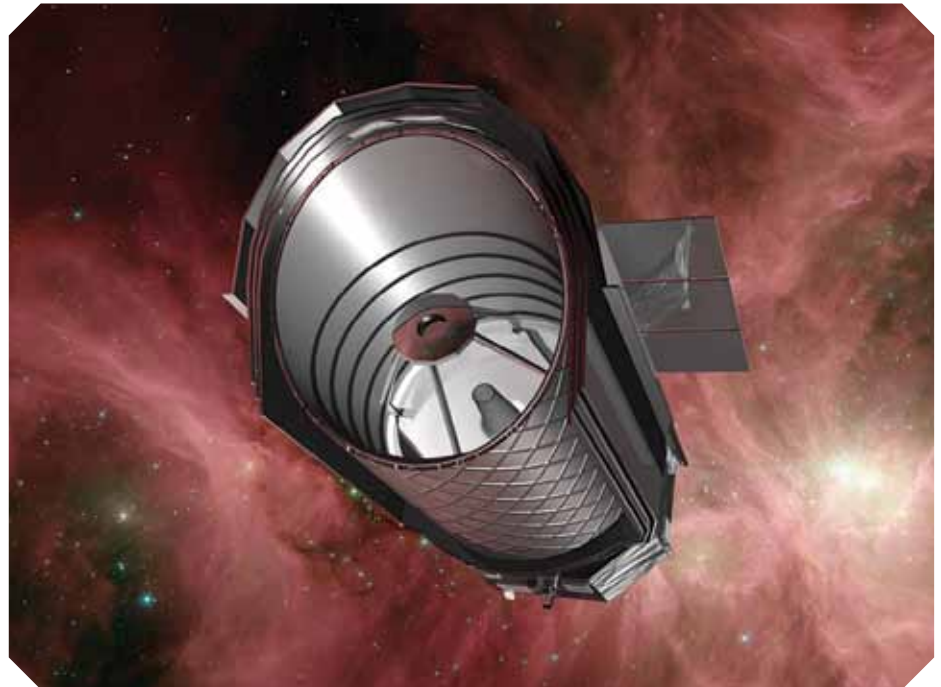


Figure 5-3. Artist's impression of JAXA's SPICA mission. [ESA]

these observatories are not expected to be launched until well into the next decade.

The LRPP notes the vitality of the Canadian FIR community, which has made important contributions to Herschel, and which is reaping the benefit of successful participation in the mission. In the same way that Herschel/SPIRE is essentially an extension of JCMT/SCUBA/FTS into space, so too is SPICA/Safari an extension of SCUBA-2/FTS-2 into space. Canadian expertise in Far IR space astronomy is thus heavily influenced by, and synergistic with, Far IR ground-based endeavours. As a result, Canada is well positioned to become a partner in SPICA.

**Recommendation 26**  
*The LRPP gives Canadian participation in SPICA very high priority under medium-scale space projects.*

### 5.4 Micro- and Nano-satellites

Canada is a world leader in technology for small (size of a shoe-box to size of a suitcase) satellites; the CSA should consider investing heavily in the technology, infrastructure, and the training of individuals to cement our international leadership role. Unique reaction wheels and pointing technology have been developed at the University of Toronto and by Canadian industry.

The MOST microsatellite (§3.2) is a clear example of what Canadians can accomplish in space with a small payload, a relatively small budget, and excellent ideas. Canada's commitment to small satellite missions has been emphasized by the CSA, and one example of this is CSA's hosting of the 2010 *Workshop on Sub-orbital Platforms and Nanosatellites*, which

has just released its report<sup>15</sup>. The report from this workshop highlights the need for additional investment in infrastructure, the main component of which is to put in place the CSA's FAST (Flight for Advancement of Science and Technology) program, which will encourage development of nanosat-class missions on short timescales. Canada is well poised to succeed on short-timescale nanosat development, particularly through the newly created Microsatellite Science & Technology Centre (MSTC) at UTIAS.

The need for steady funding streams for micro/nanosat development is evidenced by the fact that Canada's follow-up commitment to the successful MOST mission has been slow, not for lack of ideas, but rather for lack of a funded, coherent program. The technological successor to MOST is NEOSat (the Near Earth Object Surveillance Satellite). This satellite (launch 2011) will systematically discover, track and determine orbits of near-Earth asteroids and comets, focusing on those in near-Sun orbits.

The scientific successor to the MOST microsatellite is the BRiGht Target Explorer (BRITE) mission. BRITE is actually a constellation of nano-satellites, and funding for Canadian participation was recommended through a competitive peer review by CSA. BRITE will be comprised of 6 nano-satellites that will capture the light shed by luminous stars and in turn shed light on their structures and histories, uncovering unique clues to the origins of our own Sun and Earth.

The BRITE nanosats will measure the brightness and temperature variations of the brightest stars in a selected area on the sky, on timescales ranging from hours to months. BRITE is based on pioneering Canadian space technology and Canada is a partner in the project (and is building two of the satellites), together with Austrian and Polish space scientists.

There are many ideas for longer-term Canadian-led micro/nanosatellite missions (see the report of the 2010 CSA Workshop on Suborbital Platforms and Nanosatellites for examples). One interesting proposed mission is the OCLE-DOCLE (Oort CLOUD Explorer – Dynamic OCCuLation Experiment), which will detect changes in the brightness of background stars as they are eclipsed by icy bodies in the outer solar system.

The LRPP endorses the concept underlying CSA's funding strategy (currently known as FAST), which is that modest but steady funding will allow the development of several missions over the next decade. As the decade progresses it will be important to ensure that CSA's funding for such missions remains commensurate with their cost. For example, a single nanosatellite telescope mission would cost \$2-4M per satellite (with several nanosatellites operating in tandem, the total cost lies in the \$10-20M range), while microsatellite astronomy missions may cost \$10-30M.

Finally, the LRPP reinforces the point that modest but scientifically exciting missions should be able to develop (growing from a good idea to launch) on very short (i.e. several year) timescales, given Canada's proven technological leadership in areas critical to these missions (e.g. fast, accurate pointing of low-power and low-mass payloads). Such timescales are commensurate with graduate education, thus offering outstanding opportunities to grow future space experimentalists. Canada's growing expertise in space metrology and attitude control systems is particularly well-suited to micro- and nanosatellites, and investment in these areas would also be helpful for securing Canadian participation in larger missions in the future.

### **Recommendation 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.*

<sup>15</sup> <http://www.asc-csa.gc.ca/eng/events/2010/wspn.asp>



## 5.5 Balloon Missions

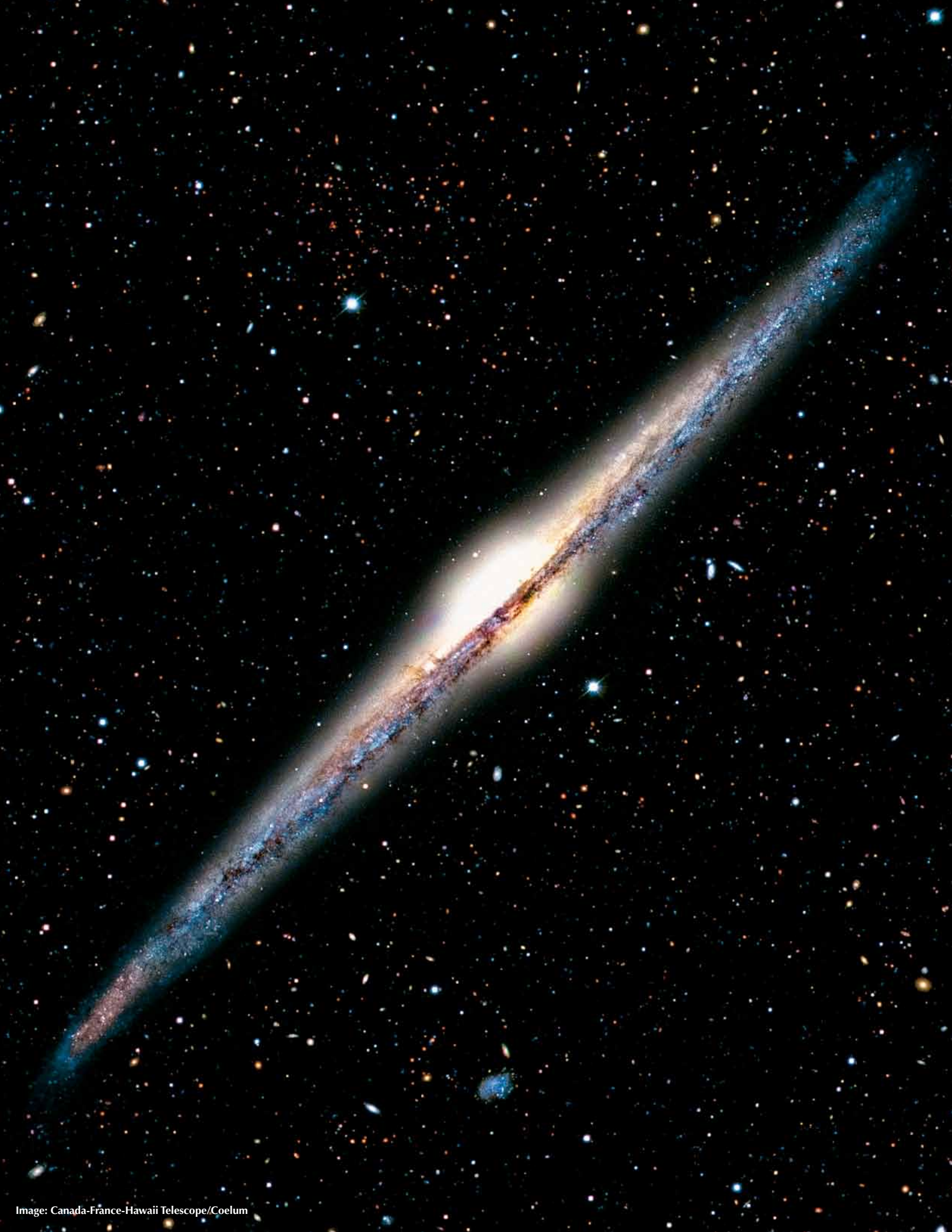
Stratospheric balloons provide one of the fastest and lowest cost paths to the space environment that is so essential for astronomical observations at many wavelengths. Results from balloon missions often provide a first look when advances in technology or fresh ideas open new observational windows. For example, BOOMERANG made accurate measurements of the first acoustic peak in the Microwave Background, establishing the spatial-flatness of the Universe, many years before the first WMAP results were available. Similarly BLAST made revolutionary FIR observations of distant starburst galaxies two years before Herschel began observations. Canadians played key roles in both of these missions. Today Canadian research groups are involved with several important balloon missions including BLASTpol, a polarization sensitive version of BLAST, and EBEX

and SPIDER, both missions designed to map the polarization anisotropy of the Cosmic Microwave Background.

Nearly as important as the science return for these missions are the training and technology development opportunities they provide. Higher levels of risk are tolerable for the low-cost balloon environment than for satellites. This allows new technologies to be flown and demonstrated – such as the polarization sensitive bolometers that were used in BOOMERANG, which are now deployed on the Planck satellite. The timescale of a balloon experiment is well matched to the length of a typical PhD, allowing students to participate end-to-end in the experiment design, commissioning, observations, and analysis. Individuals trained on balloon platforms end up as leaders in all aspects of space astronomy – e.g. those trained on BOOMERANG and BLAST who are now playing leading roles in WMAP, Planck, and Herschel.

### **Recommendation 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.*



## 6. Funding and Governance

### 6.1 Funding of Canadian Astronomy – Introduction

Canadian Astronomy is funded through a number of agencies and organizations, including:

- **National Research Council**

**Canada** – NRC’s responsibility is, through an act of parliament, to “operate and administer astronomical observatories established or maintained by the Government of Canada”. NRC’s Herzberg Institute of Astrophysics (§3.3.1) is involved in many of the large astronomical instruments (both optical and radio) under development for the community. HIA has a significant core of astronomers and engineers who are involved in astronomical research and instrumentation. To a large extent HIA is Canada’s “National Laboratory”. NRC differs from all the other agencies in that it has a management role in addition to a funding role.

- **Natural Sciences and Engineering Research Council** – NSERC funds a number of grant programs for university-based scientists, including individual and team Discovery Grants, and equipment grants. It also funds CITA through an MRS grant, and post-doctoral fellowships and graduate scholarships.
- **Canadian Space Agency** – The CSA is responsible for funding space- and balloon-based missions, including those related to astronomical research. In the past CSA has focused on mission (i.e. hardware) costs; more recently CSA is increasing its commitment to funding “downstream” processing and research from its satellite missions. For example, CSA funds 4 FTE’s at STScI, Baltimore for JWST preparations, 1 FTE and 1 PDF in astronomy at its headquarters, and has embarked on PDF and Chair programs for space sciences.
- **Canadian Foundation for Innovation** – CFI funds infrastructure for

university-based scientists. For example, it has supported the construction of SCUBA-2 on the JCMT, and engineering design for TMT.

- **Canadian Institute for Advanced Research** – Through its Cosmology and Gravitation Programme, CIFAR brings together outstanding researchers, both Canadian and international. CIFAR funds faculty chairs both at the junior and senior levels.

With the exception of CIFAR (which is partly funded privately), these agencies are all completely federally-funded. Funding trends over the past 20 years are shown in Figure 6-1, and tabulated in Appendix B. A few facts should be noted regarding this figure.

- The funding plotted in this figure is not adjusted for inflation. From Bank of Canada statistics, inflation is estimated to be 48% 1990-2010, and 22% 2000-2010.
- NRC funding is presented without salaries; this is for comparison with other sources of funding, which generally do *not* include a salary component. (For example, faculty salaries for Canadian university astronomers amount to very approximately \$20M, paid by provincial governments and subsidized by federal transfer payments.)
- NRC non-salary funding has remained fairly constant over the past decade, after a series of cuts in the early 1990’s. In inflation-adjusted dollars, this corresponds to a steady decrease in HIA’s budget.
- The large increase in CSA’s astronomy budget is due to the construction phase of JWST.
- NSERC’s budget shows two spikes in the 1990’s, corresponding to construction funds for Gemini. Since then there has been a steady increase in the

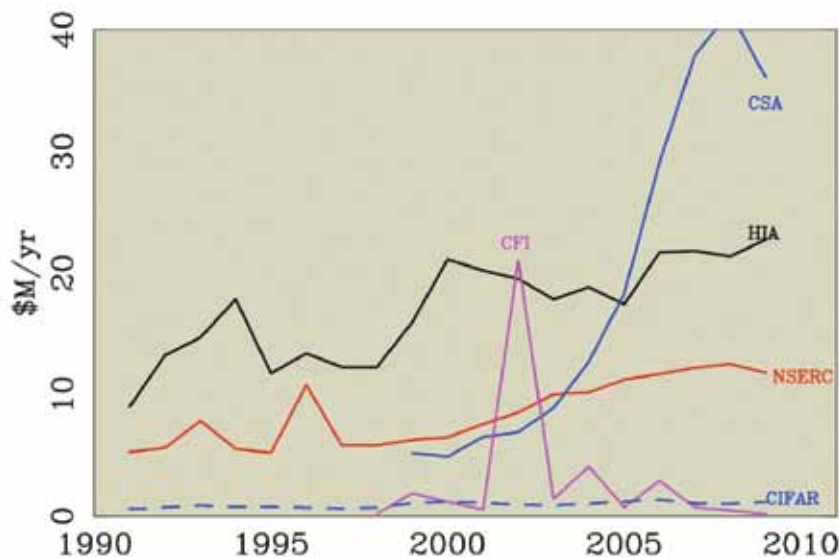


Figure 6-1. Funding of Canadian astronomy over the past 20 years. Solid black: NRC-HIA (without salaries); solid blue: CSA; solid red: NSERC; solid magenta: CFI; dashed blue: CIFAR. See text and Appendix B for details. Data in this figure is *not* corrected for inflation.



NSERC astronomy budget; but allowing for the large increase in the number of NSERC grantees in astronomy, and also inflation, NSERC grants have decreased per grantee. This is discussed further in §6.4.1.

- The spiky nature of CFI funding is due to funding for SCUBA-2 (§3.1.4) and TMT R&D (§4.1.1).

There are other sources of “non-traditional” funding that impact Canadian Astronomy:

- CANARIE has funded two astrophysics programs related to high speed computing in their “Network-Enabled Platforms” program. Insofar as Astrophysics is a major user of high speed and distributed computing, we expect usage of such programs to continue.
- NRCan funds the Polar Continental Shelf Program, which indirectly funds astronomy through a co-operative arrangement; this has provided logistical support for the Ellesmere Island Site Testing program (§4.2.3). Environment Canada has also indirectly contributed

to this project by providing field support through its base at Eureka.

- Provincial governments provide matching funds for CFI grants. FQRNT acts as a granting agency in Québec.

Some of these funding sources are considered in more detail in §6.4.

## 6.2 Canadian Astronomy Funding in an International Context

Canada’s success on the astronomy world-stage is undeniable. Has this success been achieved because Canada spends proportionally more on astronomical research than other countries?

To address this question we examine astronomy funding for the following G8 countries: France, Germany, UK, US, and also the non-G8 country, Australia (a good comparison for Canada, having almost exactly the same GDP per capita). We

restrict our consideration to annual operations funding and amortized construction costs only. This avoids biases that a single large development cost announced in one fiscal year would produce. In Canada the funding for 2009-2010 was: \$12M from NSERC programs, \$36M from the CSA, \$2M from Perimeter Institute, \$1M from CIFAR and \$36M from the NRC, for a total of \$87M (see Appendix B). This includes both the costs of facility operations, and the cost of doing research at universities (grant funding) but does not include faculty salaries (although it does include HIA salaries). As a fraction of the 2010 GDP of \$1556B this amounts to 0.0056%.

For these conservative spending estimates (see Appendix E and Figure 6-2), the G8 nations listed average 2.2 times more spending than Canada, while even Australia, widely viewed as a fiscally conservative country, still spends almost 40% more than Canada, *even after including Canada’s exceptional 2009 expenditure on JWST* (see Figure 6-1).

It is worth noting that a more typical CSA spending budget of \$10M would make the ratios 3.1 (G8 vs. Canada) and 2 (Australia vs. Canada). These findings place the extraordinary achievement of Canada in astronomy in an even more remarkable light: the success of Canadian astronomy has been achieved despite a funding envelope that, relatively speaking, is significantly smaller than other G8 countries.

Considering that for six months in 1918 Canada had the largest operational telescope in the world, namely the Plaskett telescope at the DAO, and for a significant period after 1935 had two of the largest telescopes (Plaskett and the David Dunlap Observatory) in the world, the current funding climate is not indicative of past trends. It is therefore instructive to look at the evolution of world spending on astronomy.

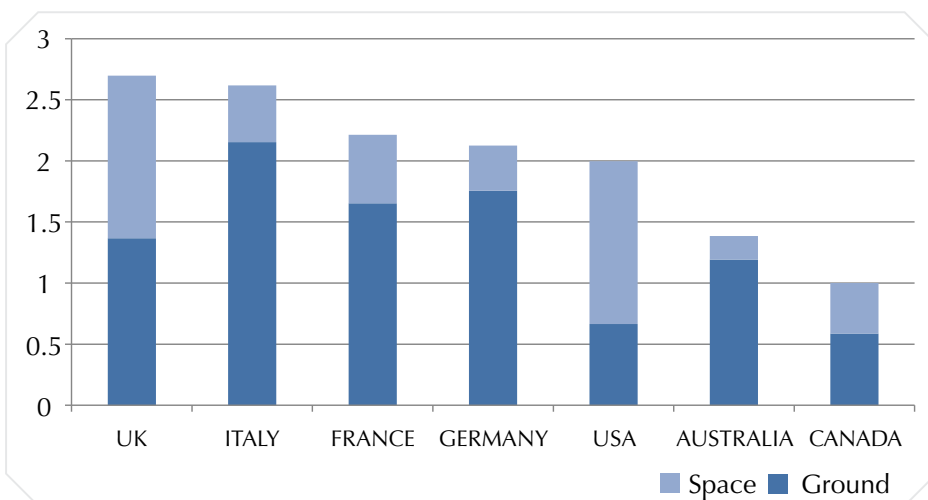
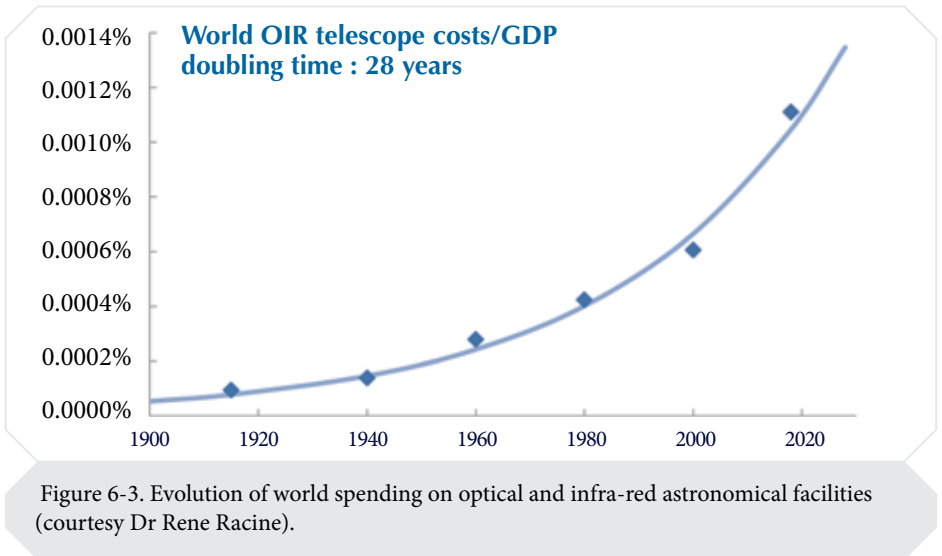


Figure 6-2. Annual spending by various countries as a relative fraction of GDP compared to that spent by Canada. A separation into ground- and space-based funding is also given. See information in Appendix E for details.

Figure 6-3 shows the evolution of world spending on ground-based optical and infra-red telescopes as a function of total GDP. The values for 2020 are projected on the basis of the estimated costs for TMT, GMT and E-ELT and assume they are all built this decade. Note that these are capital investment costs for major facilities only, averaged in 10 year periods. Direct comparison to current operational budgets is complicated by the growth in different sub-disciplines of astronomy and the variability in operational versus capital costs. As a rule of thumb, over 10 years operational costs match the initial capital investment.

Notably, the doubling-time of funding as a fraction of GDP is broadly coincident with the doubling in the diameter of optical telescopes. The time between the Hooker 2.5m and Palomar 5m was 30 years. From the Palomar 5m to the Keck I 10m took slightly longer at 45 years. Projecting forward from the completion of Keck I in 1993



suggests a 20m telescope should be built around the 2020 time frame.

The trend of increasing costs is mirrored in other subject areas such as particle physics. For example, capital costs for the Large Hadron Collider likely exceed 6B Swiss francs, while the earlier

LEP collider cost 1.3B Swiss francs. The annual operations budget of CERN has now grown to slightly under \$1B. These increasing costs have required increased international collaboration. Astronomy has followed this route as well.

Increasing costs inevitably lead to the question: how does the effectiveness of the facilities scale against available funding? One instructive statistic is to compare the area of the telescope mirror (its light gathering power) against GDP (normalized to 2009 values). In Figure 6-4 the historical evolution of this trend for Canada and the US and combined ESO countries, is shown. The final data points for Canada assume it participates in a large VLOT project. The net impact of Canada not participating in an VLOT project is clear: telescopic power that is a full order of magnitude lower than other countries as a function of GDP. Even today the available power as a function of GDP is under half that of the US, and 1/3 lower than that of the ESO countries.

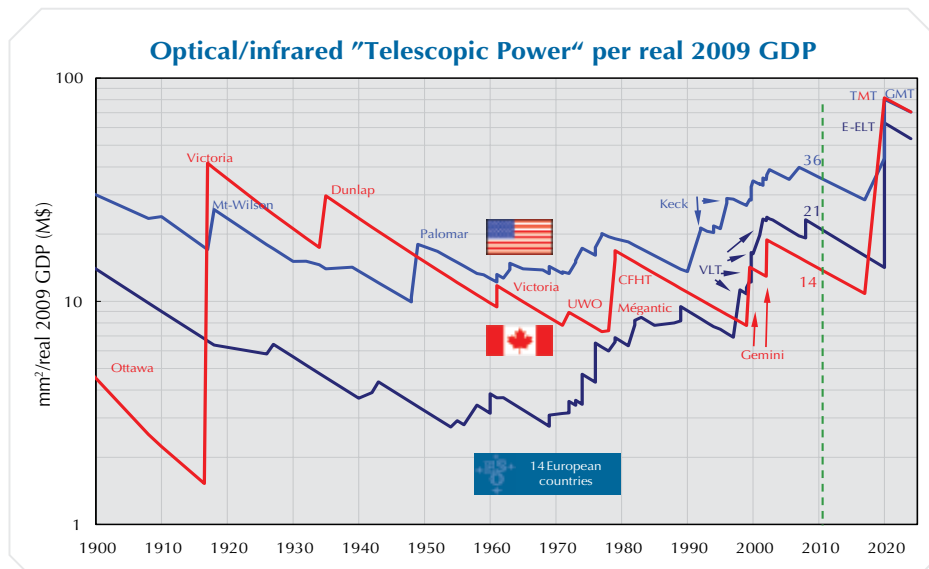


Figure 6-4. Evolution of ground-based optical/infrared “telescopic power” (total collecting area of all OIR telescopes) as a function of GDP for Canada, the US and European members of ESO.

The trend is clear: other countries have already leapfrogged us in terms of investment and facilities. From 1975 to 2000 Canada invested \$300M (2009 adjusted)

in capital and \$11M per year in facility operations. A similar investment in the 2000-2025 timeframe will not enable us to participate in the upcoming global observatories. Staying competitive requires doubling the previous investment.

## 6.3 Governance of Canadian Astronomy

First of all, it is important to understand what is meant by “governance” in the context of astronomy in Canada and the LRP, since astronomical research by its nature cannot be “governed”. There are two primary contexts relevant to LRP2010 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, JCMT and, in the near future, ALMA. The second context relates to grants and contract funds to conduct research with these and other facilities.

The LRP2000 was not concerned with issues of governance, since the landscape then appeared to be reasonably stable and predictable. NRC served as the sole agency concerned with major facilities, and NSERC the sole agency for research grant funds. In the intervening ten years the landscape has changed significantly. These changes have been outlined in the introduction (§1.3) and in other parts of this report. However, some bear repeating because of the relevance to governance:

1. Despite many successes in the early stages of the LRP2000, there was little new funding for the second half decade of the LRP; NRC had to provide significant funds from its own budget to “cash manage” its LRP activity – an unsustainable process.

2. Canada is not keeping pace with other economically developed countries in the support of astronomy (see §6.2).

3. NRC’s strategic priorities have been changing recently to focus on industrial support in pursuit of national priorities, with emphasis on health and wellness, sustainable energy, and the environment. This recent focus has created uncertainty in the astronomy community regarding NRC’s ability to provide for the needs of astronomy.

4. There has been a developing sense that NRC and the CSA need to co-operate more effectively in the area of space astronomy.

5. There is a need for a more effective mechanism for the astronomy community to be heard in Ottawa. The Coalition for Canadian Astronomy serves well in this capacity but there needs to be a regular mechanism established by the Federal Government for setting priorities for “Big Science” initiatives.

6. Better coordination among the various funding agencies could provide more effective support for astronomy research. The Agency Committee for Canadian Astronomy (ACCA) represents an important first step in rectifying this deficiency, but more needs to be done.

An important process in dealing with many of these issues of governance was the Governance Workshop held in Ottawa on June 2, 2010 and sponsored by ACURA and the LRPP. The workshop was attended by many of the players in a position to effect change, and served to air the primary concerns, and to resolve that more meetings should be held to propose solutions. The workshop presentations and subsequent discussion brought out some further points of interest:

1. Governance and funding are different issues (though perhaps not totally unrelated).

2. All agency representatives noted that they had insufficient funds to maintain astronomy at its pre-eminent position internationally.

3. Canada is a small country and there is no way to smooth out the peak demand for large projects.

4. NRC cannot act as an advocate or champion for astronomy facilities. The universities will have to “step up to the plate” in a more effective manner.

Thus it is timely to consider a new model of governance for Canadian astronomy that addresses as many of these issues as possible. Such a model needs to be aimed at satisfying the needs of all stakeholders, while achieving a more stable and predictable environment for managing and funding Canadian astronomy. We consider a model that would go a long way to achieving this by suggesting new roles to be played by the relevant organizations.

### NRC’s future role in Canadian astronomy

Under any new governance model, Canadian astronomy will continue to need a national laboratory for instrument development and data archiving. Thus HIA will remain as indispensable as it is now. HIA is currently managed by NRC and carries out NRC’s parliamentary mandate to operate and administer observatories established or maintained by the Federal Government. NRC-HIA has performed exceptionally well in this role, as is evident from the recent 2009 review of HIA and the annual HIA Advisory Board reports. These considerations and the benefits of the stability offered by a large organization argue that NRC



should continue to manage Canada's observatories through HIA.

### A role for ACURA in a new governance model

The existing management of observatories by NRC does not include a formal role for Canadian universities, despite the fact that the great majority of users are from this community. That is not to say that there are no mechanisms for interactions. Existing interactions with HIA include partnerships in designing and planning new facilities such as TMT, where both HIA and the universities have delivered resources. HIA also consults the university community regularly, both through annual meetings of the HIA Advisory Board, at CASCA meetings, and through the LRP process which it co-sponsors. However what is lacking is a role in the management of HIA itself. During the decades since HIA was established, Canadian universities have attracted major funds for astronomy (e.g. SCUBA-2 and TMT design) and have developed world leading expertise in the area of instrumentation. There is a strong sense in the community that a role needs to be found for ACURA in the management of HIA, to look after the interests of the universities in operating facilities they use. ACURA has indeed formally raised with NRC the desirability of a cooperative management role in HIA, but there has yet to be a meeting of minds. The LRP is perhaps an appropriate place to raise the subject to stimulate broader discussion and perhaps widen the scope of the possibilities.

One often suggested response is a model like TRIUMF, where NRC acts as a conduit for funds from the Federal Government and where the universities use these funds to operate the facility and conduct research funded by NSERC. Whereas it is certainly premature to reject such a

radically different arrangement, such a model has the disadvantage that it would not fit well with NRC's mandate to operate the national observatories. NRC's role would be to simply transfer funds. In addition, TRIUMF does not have A-base funding, and its budget is considered anew every five years by the Federal Government. Thus the TRIUMF model would not be as stable or predictable as the current arrangement with NRC.

An alternative and perhaps better response would be for NRC to contract HIA's management to ACURA, thus giving ACURA a direct role in governance and preserving NRC's role as mandated by parliament. This model would be similar but not identical to that for the operation of U.S. national observatories in which NSF contracts with university organizations AUI and AURA (the analogues of ACURA) to operate these facilities. This model has been particularly successful in the U.S., especially for radio astronomy. An important difference in Canada is that NRC is fundamentally a research organization managing its own institutes, whereas NSF is not. It is important to emphasize therefore that the purpose would be to engage the major stakeholders in governance, to develop synergistic relationships with university labs, and to provide a more effective voice to the Federal Government in promoting and managing the national astronomy program. It would not be intended to replace or usurp the role of NRC, which already has an excellent track record in managing HIA. The contract to ACURA would be for a fixed term with specific terms of reference, that could be terminated or revised if found to be unsatisfactory.

Such a model would give Canadian universities a new and significant voice in managing Canadian facilities, but it is also important that ACURA be adequate-

ly prepared for such a role. ACURA needs to ensure that it has the confidence of the Federal Government to engage in management of HIA. In addition, ACURA needs to be sure that there is the appropriate mix of senior scientific and administrative faculty on its Board and Council, and on the proposed HIA Management Board.

### Cooperation between NRC, ACURA and the CSA in a new governance model

There is prevailing sense in the community that a mechanism is needed to increase the level of cooperation between the CSA and NRC; this is essential for global planning in astronomy. For example NRC should encompass in its mandate the operation of space-based observatories similar to that for ground-based facilities. The CSA and NRC should also cooperate in a more integrated and synergistic way in the design and development of space astronomy instrumentation.

In the context of the contract model discussed in the previous subsection, NRC and the CSA could in principle jointly operate HIA by contracting the management to ACURA. While this seems like an attractive arrangement, a possible difficulty is the appearance that NRC and CSA would be altering their respective mandates by sharing the operation of government observatories. It thus might be troublesome to arrange. An alternative would be provision for the permanent appointment of a CSA member to the ACURA Board responsible for managing HIA. This would be easier to arrange, and would provide opportunity for regular interaction among CSA, ACURA and NRC, particularly since NRC would in all likelihood have an ex officio member on the Board as well.

## The roles of NSERC and CFI in a new governance model

In order to promote opportunities for discussion of funding astronomy projects on all scales, and in particular to keep channels open for interagency coordination on funding astronomy, NSERC and CFI could be offered standing invitations to attend HIA Management Board meetings and to participate in meeting discussions. Once again, since NRC would likely have a member ex-officio on the Board, all funding agencies could be present at key Board meetings. Discussions at these meetings could inform the ACCA of progress toward cooperation in funding astronomy, thus advancing the goal of coordinated support for astronomy. Accordingly, the LRPP makes the following recommendations:

### **Recommendation 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.*

Although the above recommendation is specific, further discussion and perhaps a widening of the scope of possibilities may also be valuable, given the importance of this issue and its long-term ramifications. It should also be noted that HIA plays many roles in Canadian astronomy (research leadership, instrumentation development – e.g. §3.3.1) and these roles should be preserved in any new governance model.

## The need for a mechanism to fund Big Science

As alluded to earlier in this section, Canada lacks a mechanism for funding major science projects, in excess of \$100M. This is a concern to all disciplines in the country that require major facilities on this scale. The lack of an adequate mechanism causes severe stress within the astronomy community, since the process of seeking funds for individual projects is at best a murky one, requiring approaches to government by a lobbying process. The lack of clarity often leaves the stakeholders in a position of uncertainty and frustration. A mechanism for funding such large projects is badly needed and should include a defined budget and ground rules to enable the affected communities to plan such projects more effectively.

Accordingly, the LRPP makes the following recommendation:

### **Recommendation 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.*

## 6.4 Discussion of individual agencies

Previous sections have focused on the important role of NRC in providing observational infrastructure to Canadian astronomy. We now discuss in turn the other agencies that make vital contributions to the success of our enterprise.

### 6.4.1 NSERC

NSERC represents one of the most important sources of funding for astronomy in Canada. Although NSERC contributes less than NRC and CSA to Canadian astronomy research, it plays a unique role by focusing on the University sector, with an emphasis on funding people that use the available infrastructure. Of the funding for astronomical research in Canada in 2009-2010, approximately \$11.8M per year came from NSERC, including grants, scholarships and fellowships, and chairs. Of this amount, \$7.2M was in grants, \$3.0M in chairs, and \$1.6M in scholarships and fellowships. This funding was provided to Canadian researchers via several different granting programs: Discovery Grants (individual and team), Project Grants, Research Tools and Instruments Grants, and Major Resources Support.

#### **Discovery Grants:**

At the heart of astronomy research funding is the Discovery Grants (DG) Program, the largest individual program of NSERC. DGs represent approximately 70% of all Canadian astronomy research

funding. DGs fund basic research, recognizing, in the words of NSERC, that “creativity and innovation ... are at the heart of all advances in research, whether made individually or in teams”. Astronomy garners approximately 1.6% of all DG funding, while representing approximately 1.4% of all DG awardees. The average DG for astronomy is now \$36,095, compared to \$29,555 in 1991. Allowing for inflation (48% from the CPI index), this is a drop of 17% in average DG funding. Since 2005, average astronomy DGs have dropped by 5%, which corresponds to a decrease of 12% after inflation adjustment.

Until 2009, evaluation of astronomy DG proposals was done by a committee, Grant Selection Committee (GSC) 17, which reviewed all astronomical as well as space-physics proposals. In 2009, a major evaluation restructuring was completed, in response to a blue-ribbon panel report that suggested changes in response to the need to better handle interdisciplinary proposals. In this new “conference model” approach, astronomy is included in a larger “Physics” category, with a much larger team of evaluators having a wide variety of expertise. In the conference model, review panels are flexible to ensure appropriate review of proposals that may span traditional boundaries between disciplines.

The LRPP asked how has this major departure from the previous evaluation scheme impacted on astronomical funding. This is an important question given the degree to which Canadian astronomers rely on DGs as their primary funding source. With only one competition having occurred since the restructuring, it is premature to draw conclusions; clearly more information is needed.

### **Recommendation 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.*

### **Special Research Opportunities**

The 2009 cancellation of NSERC’s Special Research Opportunities Program (SRO) is of particular concern to astronomy. The SRO program, which began in 2003, was created to “support unique, emerging research opportunities that are timely, urgent, high-risk or have a strong potential for breakthrough that will be of substantial benefit to Canada”. Since 2003, the SRO program funded 117 projects, for a total of \$11.9M across all NSERC-funded research areas. Astronomy was by far the greatest beneficiary of this funding, having garnered \$2.8M of these funds, or 23% over the lifetime of the program. This contrasts sharply with astronomy’s 1.57% of all Discovery Grants. Of the top 3 largest SRO grants, 2 were to astronomical projects (TMT, SKA). Astronomy’s enormous domination of the program is likely due to the fashion in which important astronomical projects arise and succeed in Canada: through clever capitalizing on timely and exciting opportunities, usually in international collaborations. *The cancellation of NSERC’s SRO program had a greatly disproportionate impact on astronomy compared to other NSERC-funded areas, and hence is of significant concern. Indeed, just as the NSERC SRO program was being cancelled, CSA-sponsored*

DWGs were urging CSA to create just such a program because of its potential importance to space-based astronomy, for these same reasons.

The LRPP urges NSERC to consider the disproportionate impact of the SRO program’s cancellation, taking note of the unique needs of the astronomical research community. One possibility is for NSERC to partner with CSA and create a “Mission of Opportunity” program similar to NASA’s. This, however, would not be appropriate for funding ground-based projects of opportunity (which represented the vast majority of SRO-funded astronomy projects); some other mechanism for enabling Canadian researchers to respond to exciting and unique opportunities is sorely needed. In §7.3 we recommend a new project-oriented PDF program that would go a long way towards replacing SRO grants.

### **Major Resource Support Program**

In 2009 the MRS-I program was restructured and replaced by the current Major Resource Support (MRS) program, in order to focus support for major resources that are “unique on a national or international scale”. The MRS program currently provides significant support to astronomy, primarily via its funding of CITA PDFs and National Fellows, as well as other CITA activities, at a level of \$1.1M per year.

Although the transition to the current MRS program had no effect on CITA’s funding, the same is not true of other astronomy programs. MRS-I grants that had funded both l’Observatoire du Mont Mégantique (OMM) (since 1999), as well as a travel grant for student observing access to Canadian-supported offshore telescope facilities, were cut in 2010. (Long-term replacement funding has yet to be identified for these programs.)



This is a net erosion of astronomy funding which is of great concern.

### 6.4.2 CFI

Since 2001, CFI has funded 46 projects in astronomy, for a total of \$33.2M. By far the largest project was for Scuba-2 (\$12.3M). This astronomy funding represents 1.0% of all CFI funding projects, and 1.7% of all CFI funding to natural sciences and engineering since CFI was founded.

CFI plays a very important role in Canadian astronomy. For example, CFI has contributed in a major way to the advancement of the TMT project in Canada. This funding has resulted in the development of expertise in a number of areas critical to very large optical/infrared telescopes. Furthermore, CFI is a key player in the funding of computing infrastructure, which is of enormous importance to the astronomical community (see §3.4).

CFI also permits funding of smaller-scale projects that arise on short timescales. It is to be expected that not all of these would be visible to the LRP process, which occurs every 10 years.

To emphasize the importance of CFI to astronomy, we again consider the proposed CHIME experiment (§4.2.1). CHIME highlights the inadequacy of existing mechanisms for funding such proposals in Canada. CFI is one potential source of funds, but opportunities for proposing to CFI are infrequent. NSERC has no mechanism for funding a project on the scale of CHIME. NRC is responsible for telescope facilities in Canada, but not generally for projects of a more focused nature. Thus CFI is critical for the development of innovative ideas on short timescales. We encourage the continued funding of CFI competitions, and recommend that these occur more frequently.

CFI funds infrastructure. Some further coordination appears to be needed with NSERC to ensure that this infrastructure is exploited to its full potential for training of HQP (PDFs and students). This is discussed further in §7.

### 6.4.3 CSA

Astronomy falls under the “Space Exploration” (SE) area of the Canadian Space Agency (CSA), and is a small part of SE activities, and of CSA overall. On the other hand, of the \$542M non-salary funds made available for Canadian astronomy in the last decade, about 40% came from the CSA, primarily via funding for Canadian involvement in JWST, amounting to approximately \$145M. (We note that this JWST number is considerably larger than originally planned; CSA clearly deserves significant praise for finding these funds.) *Thus, although astronomers may not be among the CSA’s primary clients, the CSA is among astronomers’ primary sources of funding.* In this regard, the LRPP very much looks forward to the Long-Term Space Plan (LTSP) roadmap document produced by the CSA.

The LRPP applauds the CSA’s relatively rapid, tangible response to the recommendations of the Discipline Working Groups (DWGs – see §5), namely quickly providing funds for a Phase A concept study for top DWG recommendations. That said, space science data analysis is underfunded in Canada, and Canada may not be reaping the full benefit of CSA investment in missions. One solution to this problem is to associate funding with successful proposals that use CSA-funded missions; this could be done by modifying and enhancing the SSEP program, or other future programs of grants for data analysis.

The recent announcement of the Grant and Contribution Program within CSA

is potentially extremely important for astronomy. It is anticipated that the Grant and Contribution Program could yield support for key items such as:

- University chairs in strategic areas
- Clusters, or groups of researchers funded in strategic areas in common research projects, possibly similar to the NSERC strategic network grants
- Initial studies for science mission concepts
- An accelerator program to supplement existing grants to university researchers to fund more students and PDFs in space science areas

The astronomy community would benefit strongly from having better knowledge of important technology development taking place in industry. This would enhance the astronomy community’s ability to find commonalities between important science endeavours and government/industry priorities. The LRPP therefore recommends that CSA communicate to the astrophysics community as soon as possible a list of space-based technologies Canada is interested in developing. CSA could sponsor workshops on emerging technologies to connect this list of technologies to future astrophysics mission concepts, or provide an online, searchable database both of space-related technology capabilities and areas under development in Canada.

Overall, a challenge for Canadian astronomers is to ensure that JWST is not the high-water mark for astronomy funding from the CSA. In fact the LRPP is recommending a major participation in one of the Euclid/WFIRST/CST Dark Energy satellite missions (§5.1). Space science missions generally have long lead times; commitment sooner rather than later to major contributions to missions is important to establish.

One matter that underscores the difference between NASA and CSA cultures is the role of the science team. In the NASA system, the instrument team has full responsibility to run industrial contracts and deliver the instrument. CSA however awards and manages contracts themselves, and the science team is purely advisory. The essential science team role of making science-based trade-offs and changes as instruments evolve has been hard to establish, as has science team involvement in calibration and testing prior to instrument delivery.

### **Recommendation 32**

*We recommend that the CSA move towards a system that enhances the role and involvement of science teams in instrument delivery.*

The LRPP reinforces past suggestions for regular CSA Announcements of Opportunities (AOs) and Requests for Proposals (RfPs) for mission concepts or mission involvement, as well as rigorous peer review of proposals. To this end, one possibility worth considering is the development of a program equivalent to the former NSERC Strategic Research Opportunity (SRO) program: time-critical proposals for concept study for new scientific opportunities would be accepted by the CSA at any time according to well defined rules. This opportunity would require a short proposal which requests support at a level to permit collaborative work among Canadian scientists. Turnaround should be short, i.e. a decision on the proposal returned to the PI within 4 weeks, and with a final report to the CSA due at the end of a six month period.

In addition, as mentioned above, the LRPP is enthusiastic about the response

from the community to the successes of the DWG reports. These generated a significant quantity and quality of ideas, which were expected to be, and were, considered in future plans for programs and opportunities at the CSA. The LRPP believes that the CSA's contact with new opportunities can be continually freshened by the ready availability of a process similar to the DWGs.

### **6.4.4 CIFAR**

The Canadian Institute for Advanced Research (CIFAR) was founded in 1982 with a view to creating an international network of creative generalists who could interact to address some of the great challenges facing science and society. Current members include both Nobel Laureates and Guggenheim Fellows. The program is funded by private philanthropy (corporate and individual) as well as federal and provincial grants. To date it has funded 19 distinct research programs.

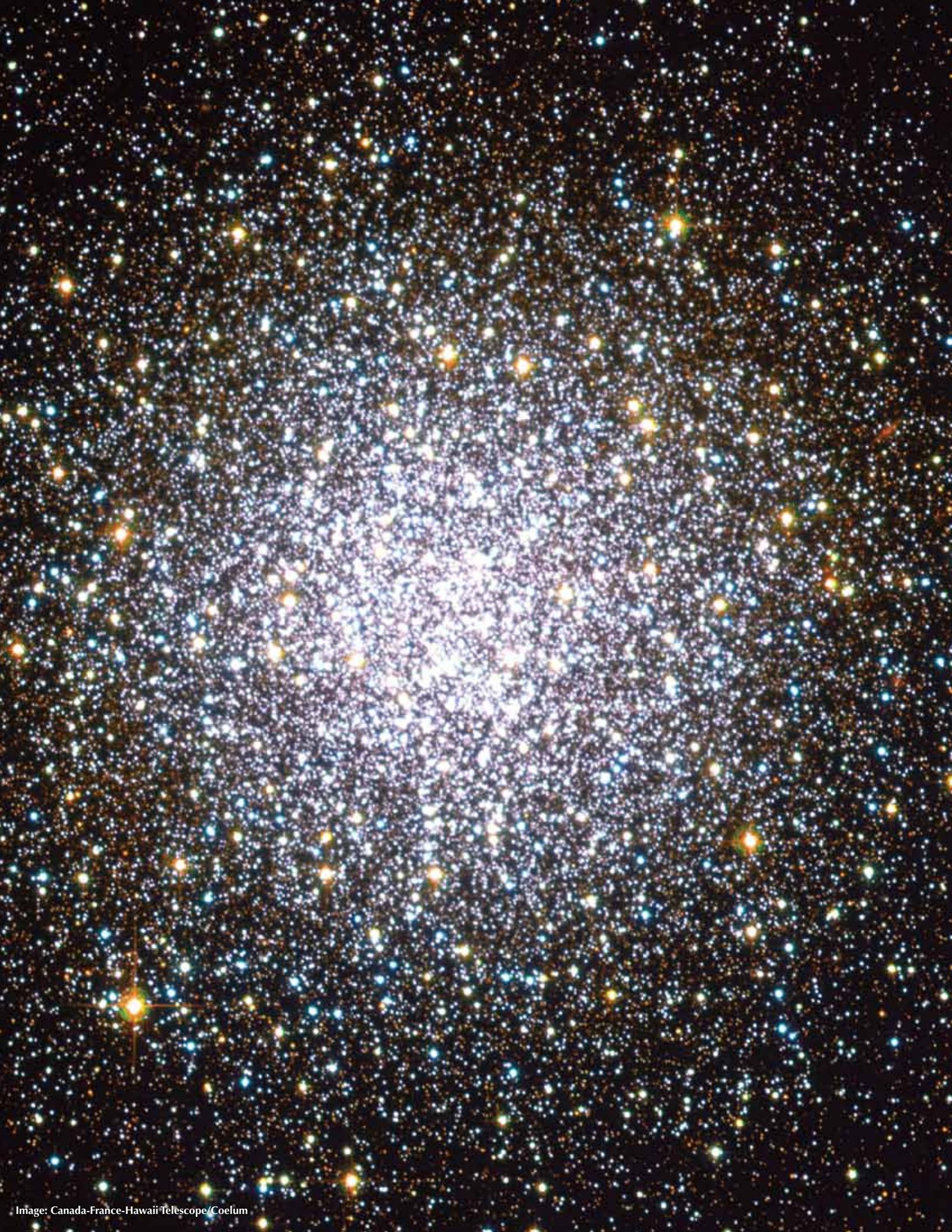
The CIFAR Cosmology and Gravity program began in 1986 and will complete its fifth successive funding cycle in 2012. This immensely successful program has now grown to encompass science areas from string theory and early Universe studies through to physical cosmology and relativistic astrophysics. In the 24 years since its inception, the program has provided over \$1 million in funding (2010 adjusted) per year to Canadian astrophysics. It has been one of the key supporters of CITA, and for the past 15 years the Director of the program, currently Prof. J. Richard Bond, has come from the CITA staff. The success of the program has contributed to its steady growth to now provide support for 14 fellows, 7 scholars and 2 junior fellows. International connections are maintained through the Advisory Board and 19 associates.

With 2012 marking the end of the fifth term, a renewal of this funding is clearly vitally important to Canadian astrophysics, with over 20 key personnel supported, at least in part, by CIFAR funds. As theory and observation become increasingly intertwined through the challenges of data analysis, a significant fraction of CIFAR members are reaching across the traditional theory/observation divide and are rapidly becoming vital contributors to observational astrophysics in Canada. This development closely mirrors the founding philosophy behind the program.

### **Recommendation 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.*







## 7. Demographics

### 7.1 Introduction and Trends

Driven by success, needs and aspirations, the Canadian astronomical community has grown markedly over the last decade. The numbers of practically every cohort of astronomers in Canada have been rising steadily since 2000. In particular, the number of tenure or tenure-track researchers in universities has risen 70% in that interval; the number of post-doctoral fellows has approximately doubled; the number of graduate students has nearly doubled, and the number of undergraduates working in astronomy research has increased nearly three-fold, all since 2000. These numbers are reflected clearly in CASCA membership numbers, with the number of regular CASCA members having increased by over 50% since 2000, and the number of student CASCA members having increased by over a factor of 3 in the same period.

Several new areas of astronomy research have also emerged since the previous LRP. These include High Energy Astrophysics, which has been the fastest growing subfield of astronomy in Canada, as already noted in §5.2. Other important areas of growth are planetary sciences and instrumentation.

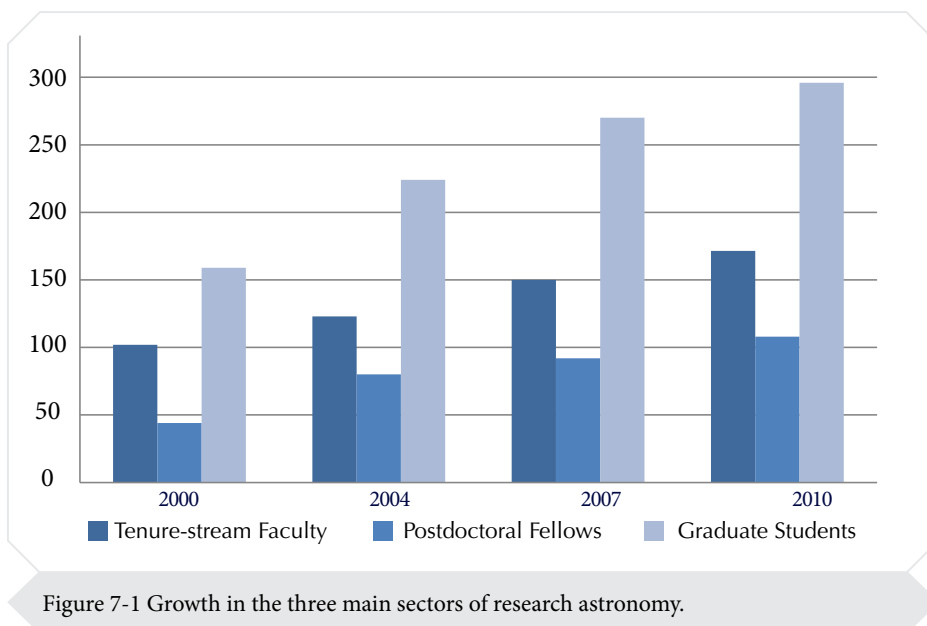
The last decade has seen an increase in university faculty working in close collaboration with Canadian industry. For example, two NSERC industrial research chairs were created in the last 5 years on subjects directly related to astronomy: one in experimental astrophysics, and another in optical design. With the advent of large projects (TMT, SKA, etc), this close collaboration between universities and industry is expected to grow.

The increase in university-based researchers provides a robust picture of the overall trend in Canadian astronomy, given that more than 80% of the

Canadian astronomy research community is university-based. By way of contrast, 70% of the Canadian operations budget for all astronomy originates with NRC, where a smaller fraction of the researchers are based. This highlights the importance of the partnering of universities with NRC and HIA, as described under *Governance* (§6.3).

Along with the well-documented growth in the astronomical research community in Canada, there has been growth in the total NSERC research grant funding of astronomy. However, in absolute dollars, the average Discovery Grant value has not changed significantly since 1991, implying a decline when accounting for inflation. This is on top of an already relatively low level of funding relative to other developed countries (§6.2).

Meanwhile productivity, both in terms of overall number of refereed papers per year, as well as per astronomer per year, has actually increased in spite of the funding decline. Moreover these same researchers are collaborating more, with the average number of authors per Canadian astronomical paper having risen by approximately 60% since 2000. This is likely because the population increase is dominated by younger and more scientifically active people, who bring with them international collaborations. Nurturing and retaining these researchers, who represent the future of Canadian astronomy, will become increasingly difficult if funding and resources do not increase. Indeed the large scale of the facilities under consideration for this LRP represent both a major challenge for Canadian funding agencies but also a reflection of the very natural aspirations of an active, productive and successful research community.



## 7.2 Student Training

Student training underpins the success and future of both astronomy, and also society in general. Training in astronomy spans numerous disciplines, including mathematics, physics, chemistry, computing and engineering. The graduates of astronomy programmes possess a vast range of skills, and the capacity to tackle a wide spectrum of problems in fields other than astronomy (e.g., engineering, finance).

The LRPP, jointly with ACURA, has surveyed Canadian universities to understand the demographics of the student population in astronomy and astrophysics. The results are in Appendix C. Below we summarize the principal points of this survey.

- As already noted, graduate student numbers have almost doubled in the past decade.
- The number of undergraduates involved in research has risen by a factor of 2.6 since 1999.
- Most graduate students (2/3) are in observational astronomy, with 1/3 in theory.
- Graduating students find employment primarily as PDFs (1/3), temporary research and lecturing positions at universities (1/4), permanent faculty or equivalent (1/4), and in industry (1/5).
- Within industry, significant employers are the financial sector and software development. Industry has played an increasing role in the education of students over the past decade.
- The involvement of women in graduate astronomy in Canada has grown rapidly over the past 2 decades, and is now approaching parity with men. This is in contrast with Physics in Canada, where approximately 20% of the graduate students are currently female.

The main issue that arises with graduate student training is funding: almost all of this funding originates in NSERC, through scholarships or through Discovery Grants to faculty. With a burgeoning student population, there is tremendous pressure on NSERC, pressure that is destined to grow.

## 7.3 Postdoctoral Fellows

Postdoctoral fellows (PDFs) are a critical contributor to the success of astronomy. Without teaching and administrative requirements, these individuals make significant contributions to research, and frequently lead research teams across the country. The skills they develop as part of this training serve them well either for the transition into faculty positions, or a shift into a different career.

Appendix D contains information from our survey, jointly with ACURA, of PDFs and PDF funding in Canada. Below we summarize some pertinent facts from this survey.

- PDF positions in Canadian astronomy have more than doubled in the past decade.
- Approximately half of the funding for these PDFs originates in NSERC. The rest of the funding is spread over several smaller sources, including CSA and CANARIE.
- A survey of a number of institutions outside Canada shows an approximate 1:1 ratio of PDF to faculty numbers. This is in contrast to the situation in Canada, where the ratio is about 1:2.
- There is a tremendous demand for PDFs across Canada. “More PDFs” was a nearly universal message heard in the LRP Town Hall Meetings.

Looking to the future, the LRPP is especially concerned that Canada’s deficit of PDFs, relative to the average of international institutions that we surveyed, will adversely impact on the science that we plan. In order to reap the full benefit of Canada’s investment in the new global observatories, particularly ALMA and JWST, new mission/observatory-oriented PDF programs need to be introduced and supported. It is particularly important to have new personnel in place when new facilities are commissioned, for two reasons. First, the early observations yield a wealth of breakthrough discoveries. Second, during these early observations much is learned about the performance of observatories and many calibration and analysis issues need to be solved. This environment is one of the best possible for HQP training: learning on state-of-the-art facilities and addressing critical operational problems.

The US has a strong history of mission-oriented PDFs. The Hubble prize fellowships in the US (17 per year now offered) have ensured that scientific rewards from major projects are fully realized. These fellowships cover a wide variety of missions beyond the HST, including Einstein, Herschel, JWST, SOFIA and Spitzer. Adopting a similar program of Canadian prize fellowships associated with major facilities would address many of the issues outlined above.

This can be achieved first, by augmenting two current programs, the CSA Space Science Enhancement Program (SSEP) and the CITA National Fellows Program; and second, by adding a new NSERC funded fellowship program that directly supports major ground-based facilities. (This project-oriented program would replace the cancelled SRO program.) By supporting data

analysis of missions funded by the CSA, the SSEP program directly meets the concerns outlined for space-based missions; the recommended 4 PDF's below is obtained by scaling from NASA's support of HST PDF's. We have already discussed augmenting the CITA National Fellows program in §3.3.4.

***Recommendation 34***

*The LRPP recommends that CSA set aside funds in the SSEP program to provide support for 4 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.*

***Recommendation 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.*







## 8. Astronomy and Society

### 8.1 Astronomy and Canada's Strategic Plan for Science and Technology

The Conference Board of Canada ranks science skills as one of the key contributors to entrepreneurial innovation and technological advancement. Investment in astronomy and teaching its underlying science helps build and maintain a scientifically literate workforce. Indeed, many students are first drawn to science by their fascination with astronomy, and then migrate to other fields of science or engineering. Investment in new astronomical facilities spurs the creation of new technologies, particularly in optical science, remote sensing, space technology, and large-scale computation. Astronomy's broad popularity has also led to the public becoming directly involved in scientific discovery through the process of Citizen Science, e.g. SETI@home, while also providing unparalleled opportunities for accessible hands-on training that leads to real discoveries.

The advantages flowing to Canada from investment in astronomy are well aligned with the present Government's science and technology strategy, as presented in the "Mobilizing Science and Technology to Canada's Advantage" document. The strategy has four central themes:

1. Promoting world-class excellence
2. Focusing on priorities
3. Encouraging partnerships
4. Enhancing accountability.

It is worthwhile showing explicitly how investment in astronomical research is closely aligned with each of these themes.

#### Theme 1: Promoting world-class excellence

Astronomy in Canada meets the definition of world class in numerous ways that have already been discussed in §2.3. To summarize, in the international arena, Canadian astronomy and space science has the highest impact of any of the sciences. Canadian astronomy ranks highest in impact of any country in the G7. Canadian astronomical facilities have had an enormous impact on the development of the field over the past few decades. And, Canadian astronomers do disproportionately well in garnering prizes and distinguished chairs, compared to other disciplines.

#### Theme 2: Focusing on priorities

Astrophysical research encompasses many of the deepest questions that confront our species, such as the origin and evolution of the Universe and the existence of life beyond our planet. The timelessness and scale of these questions goes straight to the heart of human curiosity. Important discoveries made by Canadians in these areas will define Canada's place at the forefront of those countries that have contributed fundamentally to human progress.

Canada's S&T strategy advocates investments in targeted areas that are of pressing social or economic importance to Canadians. These areas include: (1) Natural resources and energy; (2) Health and related life sciences and technologies; (3) Information and communications technologies; and (4) Environmental science and technologies. In the following sections we outline how astrophysical research, which is focused on fundamental questions, has had a major impact in these prioritized areas.

#### Priority 1: Natural resources and energy

Astronomy relies almost entirely on obtaining information through remote sensing. The image analysis techniques developed by astronomers have also been applied to interpreting images of Earth taken from space. It is also noteworthy that most images obtained by remote sensing satellites are taken using Charge-Coupled Devices (CCDs), whose early development was also driven by astronomers.

Nuclear power generation and astrophysics are closely intertwined. The historical connection is fundamental, as astrophysical research first revealed the existence of nuclear fusion, the central process that powers the Sun. Astronomers continue to make indirect contributions to this area, as the adaptive optics technology developed by astronomers plays a central role in inertial confinement experiments whose goal is to turn nuclear fusion into the ultimate clean energy source. Furthermore, the simulation codes that are now used to help design fusion experiments employ many techniques that have been initially developed and employed to simulate the extreme conditions in stars and stellar explosions.

#### Priority 2: Health and related life sciences and technologies

Astrophysical research has found many applications in medical imaging. Techniques originally developed for radio astronomy are used in tomographic reconstruction of the interior of the human body in CAT and PET scans. LASIK eye surgery uses many techniques originally developed for adaptive optics on telescopes, a Canadian research specialty. Astronomical instrument makers also played a key role in developing

keyhole cameras for laparoscopic surgery. Medical X-ray imaging uses techniques developed for astronomical X-ray imaging.

An important new source of synergy between astrophysics and life sciences is the storage and interpretation of large databases. For example, image classification techniques developed by astronomers for understanding galaxies are also being used for automated tumour identification.

Radioactive beam facilities, for example at TRIUMF, are now increasingly used for nuclear medicine. These facilities were originally developed to measure nuclear cross sections, which were used to understand the creation of elements in stars.

### **Priority 3: Information and communications technologies**

One particularly noteworthy example of astronomy's impact on ICT is the development of wireless, or so called Wi-fi networking. By 2014 the world market for Wi-fi appliances will likely be in excess of \$250 billion. Yet the basis of this technology can be traced to 1977 paper, co-authored by Dr John O'Sullivan, on techniques to help improve images from radio telescopes. Almost twenty years later O'Sullivan applied the results of his earlier work to reduce interference of radio signals used to carry computer networking and gave rise to part of the 802.11 standard.

Today the development of new detector technologies is building bridges between Canadian industry and astronomical research. Many examples of these connections can be found in §8.2 and Appendix F.

Theoretical astrophysics has also underpinned developments in parallel computing algorithms and hardware.

With simulating astrophysical systems being one of the "Grand Challenges" of the 1990s in computation, breakthrough calculations developed by astrophysicists and ICT specialists led to the wider adoption of low-cost "Beowulf" computing clusters. This work has had an enormous impact on simulation, data analysis, and data visualization throughout industry.

### **Priority 4: Environmental science and technologies**

Cosmology has been described by Lord Martin Rees as the "grandest of the environmental sciences"; the same can be said for all of astronomy. Measuring and interpreting the variability of the Sun is clearly of immense importance to improving our understanding of climate change. The variability of the Sun includes powerful coronal mass ejections (solar flares), which can disrupt electrical and communications systems. (A famous example is the solar flare-induced power outage experienced by Hydro Quebec in 1989, which paralyzed much of the province for nine hours.) Studies of nearby Sun-like stars (for example, with Canadian micro-satellites such as MOST – see §3.2) show that coronal mass ejections can be far more powerful than the 1989 event<sup>16</sup>.

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.

## **Theme 3: Encouraging partnerships**

Astronomy is among the most international of the sciences, with most major astronomical facilities being partnerships, either between countries (e.g. CFHT, Gemini, ESO, and virtually all space facilities) or between Universities/Institutions (Magellan Telescope, Keck Observatory) or even a mixture of countries and institutions (LBT, SALT, Gran Telescopio de Canarias). Future facilities (e.g. TMT, E-ELT, JWST, IXO) will continue this model, particularly as ground- and space-based telescope projects increase in scope.

At a national level, opportunities for partnership abound, particularly between government, universities, and industry. Examples include the heavy involvement of companies like COM DEV and Dynamic Structures in the development of JWST and TMT (respectively) in collaboration with CSA and the NRC. These linkages are discussed further in §8.2.

Astronomy also provides interesting examples of partnership between professional scientists and the general public. Amateur astronomers outnumber professional astronomers by about 100:1. The close partnership between professional astronomy and amateur organizations (such as the Royal Astronomical Society of Canada and Fédération des Astronomes Amateurs du Québec) provides unique opportunities for the public to connect with forefront researchers.

## **Theme 4: Enhancing accountability**

The accountability of astronomy to society is managed primarily through our work in education and public outreach. We defer a discussion of this theme to §8.3.

<sup>16</sup> In a recent study, *Severe Space Weather Events – Societal and Economic Impacts*, the United States National Academy of Sciences estimated the economic cost of a major disruption from a large coronal mass ejection at 2 trillion dollars.



## 8.2 Economic Benefits of Astronomy<sup>17</sup>

In §8.1 we addressed the alignment between astronomy activity and Canada's strategic plan for Science and Technology. In this section we address a closely related but more specific question: how does astronomy enhance Canadian economic competitiveness?

Canada's astronomy community recognizes that there is intense competition for Federal Government funding not just between disciplines, but also with competing spending priorities, such as infrastructure, health care, defence, sustainable energy and environment. That inevitably leads to two questions:

- Why should astronomy funding take precedence over other scientific funding priorities, in particular ones that at first glance appear to have greater potential for commercialization?
- How can astronomy spending harmonize with other government spending priorities?

The Coalition for Canadian Astronomy has gone to great lengths to answer both questions, highlighting the link between investments in scientific research and stimulating economic activity and global competitiveness. The Coalition has argued that major science projects, like the TMT, should be considered as important infrastructure projects, just like roads and bridges. Astronomy needs to do a better job building awareness of its contribution to R&D, economic development, and the global competitiveness of Canadian industry.

Experience demonstrates that strategic Federal Government investments in scientific endeavours like astronomy are not only beneficial, but are indeed critical to enhancing a country's competitive position, while at the same time stimulating Canadian industry and economic growth. Astronomy pushes the envelope of industry capability. This is readily apparent when looking at activity currently at the forefront of international astronomy. Astronomy is addressing the most pressing scientific questions concerning the nature of our Universe; this requires telescopes and instruments of unprecedented size, complexity and data acquisition capacity. We explore how these new and exciting demands benefit the economy through a number of themes related to the creation of opportunities: for growth and employment, for success in the international high technology marketplace, and for making Canada a centre for innovation that drives the modern economy. Much of the focus is on the most important sector, namely small and medium-sized enterprises.

### The Scale and Benefits of Canadian Industrial Activity in Astronomy

There are over 200 companies now involved in astronomy projects<sup>18</sup>. These projects have highly specialized designs and require private sector expertise to be designed and built. Those industries that can provide this requirement stand to reap considerable financial gain, sometimes into the hundreds of millions of dollars, as prior experience has already shown.

The projects identified in LRP2010 were selected mostly for their scientific benefits, but also for their potential to utilize and benefit the science and technology

strengths of Canadian industry. Economic analysis prepared by KPMG for the LRP2000 report found that Canada receives a two-to-one<sup>18</sup> direct return for every dollar invested in astronomy. Indirect returns have been pegged as high as ten-to-one<sup>18</sup> since the knowledge gained working on astronomy projects leads to spin-off technology – i.e. new and sometimes unforeseen business opportunities in sectors far removed from astronomy.

What is ultimately required is greater government recognition that investments in pure science will pay similar dividends – they may just be harder to identify at the outset. Therefore it is important to examine in more detail the spinoff technology in the astronomy context.

### Examples of Worldwide Spin-off Technology Resulting from Astronomy

The contracts and work experience that have come from LRP projects have generated new knowledge and technological developments that produce a variety of spin-offs and market advantage for Canadian industry. When working on projects, the Canadian astronomical community uses a “smart procurement” model: contractors are introduced to the engineering problems, and they in turn use their existing capabilities to find creative solutions. This procedure almost invariably leads to new business opportunities in spin-off areas. Furthermore, this process routinely requires developing new machinery and equipment, which improves global competitiveness.

<sup>17</sup> The LRPP is pleased to acknowledge the assistance of Duncan Rayner, Temple Scott Associates, for valuable advice and input during the preparation of this section. The LRPP also acknowledges input from several of the companies referred to in this section, and from NRC-HIA.

<sup>18</sup> The Coalition for Canadian Astronomy: “Federal Government Investments in Scientific Endeavours Are Critical to Enhancing a Country's Competitive Position”, response to the Competition Policy Review Panel's Consultation Paper: *Sharpening Canada's Competitive Edge*, January 11, 2008.

Examples of spin-off technologies developed from astronomical research throughout the world include:

- the development of image reconstruction techniques and sensitive microwave receivers that are used for analysis of CAT scans, magnetic resonance imaging (MRI) and breast cancer scans;
- baggage scanning detectors using technology originally developed for X-Ray astronomy satellites;
- the technology for the Netscape worldwide web browser;
- digital cameras and computer imaging;
- synthetic aperture radar technology employed by RADARSAT to map the earth in high detail, and oil exploration methods, both developed from interferometric techniques used in radio astronomy.

## Canadian success stories

The best way to understand the impact of astronomy on Canadian industry capability is to look at several specific examples of Canadian companies benefiting from astronomy projects. These examples are described in detail in Appendix F, and reveal that hundreds of millions of dollars of economic activity have already been generated by astronomy projects and associated spinoffs, and that such revenues are expected to continue and grow. The examples discussed include (geographically ordered):

ABB Bomem – *Québec City, Québec*  
 Lyrtech Signal Processing – *Québec City, Québec*  
 TeraXion – *Sherbrooke, Québec*  
 Breconridge – *Kanata, Ontario*  
 Ceravalo Optical Systems – *Ottawa, Ontario*  
 COM DEV – *Ottawa, Ontario*

Nanowave Technologies – *Toronto, Ontario*  
 Murandi Communications – *Calgary, Alberta*  
 Dynamic Structures – *Coquitlam, British Columbia*  
 Profile Composites – *Sidney, British Columbia*  
 Daniels Electronics – *Victoria, BC*

This is by no means an exhaustive list, but it is representative particularly in demonstrating how solving the most pressing questions in astrophysics is a driver for new technology that is then marketable in quite new and sometimes unanticipated contexts. (To quote ABB Bomem, “extensive knowhow from our R&D team acquired during such challenging programs is fed back into the commercial product line”.) In addition, some of the examples show that astronomy has helped to position some companies as world leaders in technology spun off from astronomy. Additional examples may be found in the LRP2000 report.

## International Developments

Given the size and scope of the LRP2010 project priorities, most of which involve multiple international partners, we must ask: Are other countries investing in astronomy? The answer is an unambiguous “yes”. Section 6.2 clearly demonstrates that, on a per GDP basis, Canada is falling seriously behind its peer nations in the support of astronomy and risks losing its enviable international position if Federal Government investment continues to lag behind that of other countries.

## The Future

Canadian scientists and their industry partners have established themselves as world leaders in the design and construction of highly complex astronomy projects,

creating new opportunities for Canadian scientists and engineers to participate in innovative international projects. This was clearly demonstrated when the American partners for the TMT sought out Canada’s participation in this initiative and asked Canada to lead the Adaptive Optics project. As mentioned previously, Canada’s DSL is also slated to build the telescope and enclosure for the TMT.

World Observatory projects have construction costs that exceed \$1 Billion, and there is the potential for a significant portion of these monies to be invested in Canada. For example, hundreds of millions in contracts to DSL and other companies could be possible if Canada continues to be involved in a large telescope project like the TMT. Breconridge Ltd. alone could win contracts with total dollar amounts in the hundreds of millions from Canada’s involvement in the SKA, especially in the information and communications technology area. These are just two examples of exciting future prospects, but by inference from the past successes, it is clear that astronomy research has great potential to contribute even more to Canada’s economic growth.

The large projects of the future will rely on industry to bring costs down through economies of scale. All the contracts described in the examples shown in Appendix F translate into jobs and income for Canadians. All are in the high tech field and many of the companies involved are small or medium-sized businesses; investment from astronomy enhances their competitiveness, and provides a unique opportunity to distinguish themselves in an aggressive marketplace. However, contracts will continue to flow to Canadian companies only if we continue to partner in international projects in basic and fundamental research such as astronomy – and that depends on continued financial support from the Federal Government for endeavours such as those described in the LRP.

In summary, astronomy is one of the few scientific disciplines within Canada that is a driver for S&T innovation and jobs in the high technology private sector. The scope of LRP2010 includes projects that provide for Canada unprecedented opportunities to build on its existing economic strengths, to innovate as a world leader in S&T, and to support small and medium sized companies. Canada's astronomy community should be bold in communicating its economic impact to Federal Government decision makers to ensure its contribution is duly recognized in the battle for scarce resources.

## 8.3 Education and Public Outreach

*"Now, let me turn to science, technology, research and development – areas that will help lead our nation into the next great phase of industrial expansion in Canada."*

*The Honourable Tony Clement, PC,  
MP, Minister of Industry*

Science is arguably more important to the future of our society today than at any point in the past. Aside from the immediate concern of climate change, economic advancement is centred on technological innovation, which relies upon advances in basic science. Astronomy is perhaps unique among the sciences: it contributes to economic growth, but it also addresses the deepest philosophical questions of our Universe's origins and future. It is thus no surprise that millions of Canadians take an interest in astronomy: in 2009 over 1.9 million "Galileo Moments" – events at which an individual discovers something new about astronomy – were recorded as part of the International Year of Astronomy (IYA).

This level of interest has far reaching implications. Many scientists and engineers speak of how their early interest in space and astronomy was a key gateway in selecting their future career. By directly fostering interest in science, astronomy is one of cornerstones of scientific literacy in our schools, itself a stepping-stone to later technical training. Astronomy is also an activity that can be shared within families: many people speak of how their interest was fostered by an interested parent or guardian. The unchanging nature of the naked-eye sky connects the young and old, and is a point of commonality among different cultures.

It is important to question whether astronomy is being effectively communicated to the Canadian public. A search of the national BBC website over the past year shows 50 astronomy related stories, while (national) CBC carried 22, and CTV News carried a mere 7. CNN recently cut its entire science and technology staff. This is a worrying trend that needs to be addressed.

The IYA in 2009 showed that, with effort, new connections and bridges can be built between people, societies and organizations. This celebration, designed to help people rediscover their place in the Universe, was an unequivocal success. With the outstanding contributions by Canada's knowledgeable, enthusiastic amateur astronomers, and many volunteers, the goal of 1 million Galileo moments in Canada was easily reached, and the final 1.9 million almost doubled the target. This success must be carried forward through continued effort and investment.

### Outreach: Communication and accountability

Astronomical research is a taxpayer-funded endeavour. There is thus an implicit responsibility for professional

astronomers to communicate discoveries to a wide audience. It is equally important to note that a visible return on investment is an important metric for governments. As the field moves forward there is also the exciting new possibility of wider public involvement in research through Citizen Science. This is an opportunity to connect the public more closely to astronomy research that should be taken up with enthusiasm by Canadian astronomers.

Outreach also requires long-term investment. IYA was a spectacularly successful endeavour<sup>19</sup>; but in a handful of years how many in the public will remember it? Maintaining a level of public awareness requires constant engagement. The Beyond IYA program recognizes this fact explicitly, as too have some university administrations, who in a wider appreciation of the science communication sphere, are beginning to adopt outreach as an integral component of professional development. The LRPP fully supports these moves.

However, while the responsibility may be there, it is not necessary for every publicly funded astronomer do outreach. Individuals with a talent for outreach should receive strong support and encouragement. Professionalism in this area is something to strive for, as successful outreach requires time, effort and some training. Fortunately, new workshops and courses in science communication and media training are emerging across the country. We encourage the community to take advantage of these opportunities; they are especially valuable for those at an early stage of their career development.

As a community we should emphasize the importance of outreach by, for example, requiring all graduate students to include an outreach component as part of their graduate training. This would ensure that all students take the time to consider the challenges of communicating their



work to the public. This would result in more outreach activities, which, assuming proper student supervision, would itself be positive, and overall would foster a broader outlook in our research community. Moreover, students with more of a talent for outreach would self-identify, and be better positioned and inspired for such work in the future.

### Recommendation 36

*Graduate programs should strongly consider adding some element of outreach, either training or project requirements, to their programs.*

## Building a Canada-wide dialogue

Outreach is fundamentally about communication, and effective communication truly requires a dialogue. To be successful, this dialogue must also occur at both local and national levels.

### Local

We have already mentioned (§3.3.3) the outreach centres at DAO/HIA in Victoria (Centre of the Universe) and at OMM (Astrolab). The support of these centres in the future is of high importance; such centres have an impact that goes far beyond the local community in fostering public awareness of science. In the future, the One Metre Initiative (OMI) is expected to play a major role in outreach in south-eastern Ontario. Equally as important as these centres are Canada's planetariums: approximately 450,000 Galileo Moments, essentially one quarter of the total, were generated through them. Continued innovation in digital projection technologies will further increase the effectiveness of

these facilities in delivering educational and inspirational programming.

The Canadian astronomical academic community is accompanied by a vast number of dedicated amateur astronomers, and even wider public interest. "SkyNews", a bi-monthly Canadian astronomy magazine, has a readership of over 80,000. The Royal Astronomical Society of Canada, which publishes its own journal, has 4200 members and 29 centres across Canada, while the Fédération des astronomes amateurs du Québec, boasts over 1750 members. There are also numerous independent astronomy clubs and societies across the country, as well as science centres in major urban locations, most with a strong component of astronomy Education and Public Outreach.

Collaborations between the FAAQ, RASC and CASCA were greatly strengthened by IYA, and many valuable links to local communities were built. Activities fostered by these links ranged from sidewalk observing in the middle of busy cities to star parties in remote parks. In total, over 3,500 activities provided opportunities for Canadians to rediscover their place in the Universe. The partnerships developed as part of IYA must be supported and nurtured.

One area in which CASCA contributed was the "Galileo Lectures". Ten highly effective communicators gave 22 public talks about astronomical research. The Galileo Moments database shows over 3,000 people attended these lectures. There is great value in continuing and promoting this program as a national annual lecture series.

School visits and interaction with teachers are also extremely valuable. Engaging with students in schools helps to break

down stereotypes, and can also be used to encourage under-represented demographics such as young female students. Providing teacher-training workshops is equally valuable as these individuals teach the largest astronomy audience: *school children*. Many provincial curricula include astronomy sections in several grades, yet teachers often feel ill-equipped to instruct this material. Multi-day workshops that provide deeper overviews of curriculum material, familiarize teachers with telescopes and star charts, and connect teachers to universities and the CSA, have been run in Ontario, Quebec and Nova Scotia. HIA's Centre of the Universe in Victoria also has a strong connection with the schools. We encourage more widespread activity.

### National

Mass media remains the primary avenue by which Canadians receive news. Over the last ten years science reporters have been systematically eliminated by a number of major news outlets as a cost-cutting measure. In this environment it is ever more important to cultivate media relationships and understand the needs of reporters.

At present Canadian astronomy does not have a significant "brand" profile with the Canadian public. Few can even name a famous Canadian astronomer. Simultaneously, with the loss of science reporters there has been a drop in the number of "media scientists", individuals who are talented, experienced and trained in mass communication. Individuals with an aptitude and integrity should be encouraged to pursue this career direction.

The Science Media Centre of Canada is a new development that should greatly improve science coverage in Canada's media.

<sup>19</sup> The LRPP acknowledges the extraordinary efforts of many people in making IYA2009 the success that it was in Canada, particularly Dr. J.E. Hesser (NRC-HIA), Canadian Chair of IYA2009.



Figure 8-1. Dr Stephane Courteau interacting with the people of Pangnirtung, NWT as part of the CASCA's Galileo Lectures series. [S. Courteau]

The SMCC ([www.sciencemediacentre.ca](http://www.sciencemediacentre.ca)) will provide support for journalists covering science stories, from topic summaries to providing contact details for scientists. Similar projects in the UK and New Zealand have been enormously successful, and likely contribute to the large number of astronomy and general science stories on the BBC website. We strongly support this endeavour and commend CASCA for becoming a charter member.

An AstronomyCanada.ca website could be a highly valuable resource. However, establishing the website is a task requiring significant initial investment, both monetary and in human resources. A distributed model of management should be used: by giving access to a number of individuals, stagnation concerns can be avoided. Once established, this website should be the focal point of careful branding campaign that ensures awareness. Provincial successes with similar websites rode on the back of a careful communications plan.

### **Recommendation 37**

*The LRPP recommends that the "AstronomyCanada.ca" website be co-developed with a brand awareness campaign led by the professional community.*

### **The importance of financial support for outreach**

The success of national outreach in the US is largely due to its funding. No less than 31 individuals are employed in outreach at the Space Telescope Science Institute in Baltimore. Across the US there are dozens more paid directly to communicate government-funded astronomical research discoveries to the public. Investments in astronomical facilities of the size advocated by LRP2010 must be matched by effective outreach to the public who make them possible. Taking proposed TMT investment as an example, 1.5% of total capital could provide support for six people over a 5 year time period. Split equally between web and story/education

development, such a team could also help in making scientists more aware of the issues facing media communication.

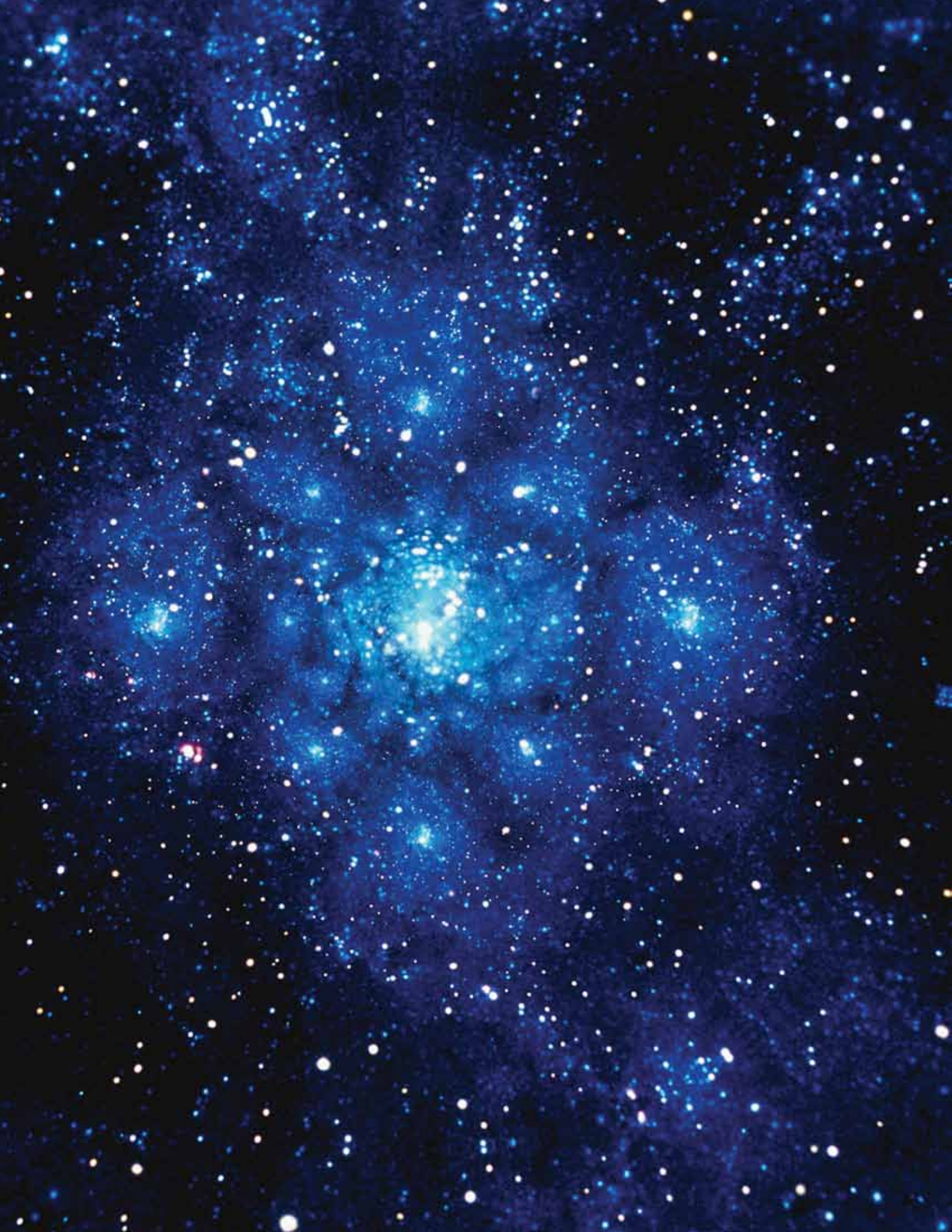
### **Recommendation 38**

*The LRPP reiterates the value of investing a 1.5% fraction of government funding of new large-scale projects into outreach.*

In 2009 in Canada only two individuals were employed full-time in the promotion of astronomical research: the Journalist in Residence at the Dunlap Institute, and the IYA coordinator (funded by the Trottier Family Foundation for two years). Two other individuals were employed part-time in relation to CASCA operations and an NSERC Promoscience grant.

The LRPP recommends that the DI continue its outreach program and encourage their Journalist in Residence to engage in the wider aspects of Canadian astronomy outreach.







## 9. Summary of Priorities

In this concluding section we summarize the priorities for ground-based and space-based facilities in different funding categories. We also consider priorities for infrastructure and human resources. *Unless otherwise noted, funding amounts below represent new funding.*

### 9.1 New Ground-Based Facilities

#### Explanatory Notes and Rationale:

##### 1. Relationship between the VLOT and SKA Projects

As noted in §4.1, the VLOT project is Canada's top priority for immediate participation in a ground-based international Very Large Facility. The SKA project is equally important and highly complementary with a VLOT but its schedule is different; it will likely be ready for construction later in the decade, or possibly in the next decade. Participation in both facilities will ensure that Canadian astronomers have

access to research of the same or similar scientific areas in two quite different and complementary wavelength regimes.

The phasing of these two projects is reflected in Table 9.1, which shows the VLOT ready for construction and the SKA in the R&D phase. The reported construction timelines for these projects are 2012-2016 (VLOT) and 2016-2019 (SKA Phase 1), and accordingly the reported schedules for VLOT/SKA have little or no overlap. For a variety of reasons the schedules for both projects may slip, but the slippage may also preserve their relative phasing. It is important to recognize also that the VLOT and SKA projects involve two distinct communities in their design and development – namely optical astronomy and radio astronomy respectively, and that even if there were an overlap in timing, both projects can be readily managed.

These points notwithstanding, the LRPP understands the challenges ahead in seeking funding approval for two projects of this scale possibly within a single decade. Indeed, the SKA and TMT projects may

both require some formal indication from partner countries of their intent as early as the start of the preconstruction phase, possibly in 2012. It will therefore be essential for the community to skillfully manage the timing and methodology of its approach to obtaining funds. For example, it may be wise to seek approval for SKA support for each of its sequential phases, rather than for the entire SKA. This approach is feasible because R&D is ongoing and funds are still needed for this purpose. Moreover the SKA is an array of many antennas and can be beneficially operated even in its early phase (i.e. phase 1). Thus it would be appropriate for the LRP Implementation Committee (§9.4) to conduct an ongoing review of progress of the SKA and to advise on how Canada should maintain a strong presence in this project.

##### 2. Medium and Small Project Rankings

These are provisional rankings and must be qualified: they are on the basis of science promise and/or long-term potential impact only. All of these projects lack a

| Category                         | Project   | \$    | \$   | Note |
|----------------------------------|---|-------|--|------|
| <b>Very Large (above \$100M)</b> | A significant share of a VLOT: highest priority is TMT if it can be built in a timely manner; otherwise E-ELT | 4.1.1 | \$5M/yr preconstruction<br>\$300M construction   | 1, 3 |
| <b>Large</b>                     | SKA R&D   | 4.1.2 | \$3.5M/yr preconstruction<br>\$56M construction (Phase 1)  | 1, 4 |
| <b>Medium (\$5M-30M)</b>         | 1. CHIME  | 4.2.1 | \$15M  | 2, 5 |
|                                  | 2. CFHT new instrumentation   | 3.1.1 | \$5M   | 2, 6 |
|                                  | 3. CCAT   | 4.2.2 | \$0.9M pre-construction<br>\$14M construction  | 2, 7 |
| <b>Small (below \$5M)</b>        | 1. Arctic site testing and telescope  | 4.2.3 | \$0.2M/yr site testing<br>\$3-5M telescope (if feasible)<br>\$0.5-1M/yr operations (if feasible) | 2, 8 |
|                                  | 2. ngCFHT R&D   | 4.2.4 | \$2M over decade   | 2, 9 |

Note: \$ amounts are for Canada's contribution only.

thorough feasibility study, technical review and cost analysis. Furthermore, each project will be subjected to rigorous peer review by the funding agencies, and will likely not all appear in the same competition. Finally, it must again be noted that other compelling cases for medium- to small-scale projects will emerge over the decade.

### 3. TMT costs

The total construction cost is in 2009 dollars, and assumes a 25% share. The capital cost of a delay in the project is roughly \$10M/yr for Canada alone. A portion of the required preconstruction funds (approximately \$2.5M/yr) has been provided as an in-kind contribution from NRC-HIA up to the present. We urge that this funding continue.

### 4. SKA costs

A significant portion of the Phase 1 construction costs may slip to the next decade. At the present time NRC-HIA is contributing approximately \$2.5M/yr in-kind towards the pre-construction costs. We recommend that this support continue. SKA pre-construction R&D is itself a medium-scale project, and this is of the highest priority.

### 5. CHIME

Costs are uncertain, as is the technical feasibility. Nevertheless this project has a very high ranking scientifically (§4.2.1), and is overall ranked at the top of medium-scale projects, subject to feasibility constraints.

### 6. CFHT New Instruments

The cost of these instruments is very uncertain at the present time; it depends on how many and which instruments are chosen, the amount contributed by CFHT itself, and Canada's share of the cost.

### 7. CCAT

The construction costs assume a 10% share in the telescope.

### 8. Arctic Site Testing and Telescope

Whether a case can be made for an Arctic telescope depends on many factors, as discussed in §4.2.3. We recommend continuation of the site-testing program in the immediate future. Should the results of this site testing confirm the existence of superb astronomical sites, then we recommend the development of a science case and a technical feasibility study for a small-to-intermediate aperture telescope. In the event of a strong science case and technical analysis, then we recommend that construction of a telescope proceed, probably in the second half of the decade. The telescope should be built in such a way as to provide a home for instruments

developed at University instrumentation labs, and the infrastructure at the site itself should be developed in a way that can support other telescopes (possibly with an international component) in the future. We again note that this work could open up a bold new direction for ground-based observing, and will be of enormous interest internationally.

### 9. ngCFHT

Depending on the timing and outcome of our request for VLOT funding, ngCFHT may emerge as a medium- to large-scale request around the middle of the decade. We recommend that \$2M be spent over the next few years to develop the concept and feasibility of an ngCFHT. This work is urgently needed before the project can proceed further.

## 9.2 New Space-Based Facilities

| Category | Project  | \$  | \$     |
|----------|--|-----|--------|
| Large    | Dark Energy Satellite (e.g. Euclid or WFIRST or CST) | 5.1 | \$100M |
| Medium   | 1. IXO R&D   | 5.2 | \$15M  |
|          | 2. SPICA   | 5.3 | \$10M  |
| Small    | 1. Astro-H   | 5.2 | \$5M:  |
|          | 2. Stratospheric Balloon Programme                   | 5.5 | \$5M:  |
|          | 3. Nanosat/Microsat Programme                        | 5.4 | \$5M:  |

### Explanatory Notes and Rationale:

Note regarding \$ amounts: The contribution for Euclid/WFIRST/CST is notional, signifying a significant involvement in the mission, possibly with an optical imager. The actual amount will depend strongly on what we contribute to the mission. Budget amounts for IXO and small projects are also notional estimates that, from

experience, are likely to be underestimated by a factor of two. We note that an accurate costing of all of these missions is urgently needed, and the CSA should set up working groups and consultants in the near future to estimate the cost of Canada's contributions to these missions. See Recommendation 21.

The rationale for the prioritization given above is based on a number of factors,

namely: (1) outstanding potential for breakthrough science; (2) synergy with the overall thrust of the Canadian astrophysics program; (3) technological readiness within the next decade; (4) alignment with the strategic goals of the Canadian Space Agency to build national capability in certain key technologies (such as metrology, precision pointing, remote sensing, and robotics); (5) likelihood of available resources. The importance of the first three factors is obvious, but the final two factors deserve special explanation.

The last decade has witnessed tremendous growth in the investment in astrophysics made by the Canadian Space Agency. In response to LRP2000 recommendations, CSA contributed over \$200M to space astrophysics missions in the last ten years (see Appendix B). The bulk of this investment has been in the JWST project, whose successful completion and launch in this decade has been assumed as a given by the LRPP in formulating all of our recommendations for new missions. The background for this investment was CSA's desire to build capability in certain key areas, and in particular to build capacity for leadership in large international space science missions, while at the same time forging closer

links with partner agencies. CSA's strategy appears to have succeeded, and one result of this investment has been a much needed and welcome strengthening of the Canadian space astrophysics community (§7).

Experience has shown that top-echelon space missions (NASA's "Great Observatories", or ESA's "Cosmic Visions"-class missions) have grown so expensive and ambitious that they generally require collaborations between several agencies. The cadence between such missions can be long, and opportunities to participate in first-rank missions occur infrequently. It is fortunate that the next large space astrophysics mission to follow JWST, Euclid/WFIRST/CST, appears very well matched to both our scientific interests and capabilities. Through partnership in the JWST mission, the CSA has devoted significant new capabilities, and demonstrated leadership in enabling Canadians to participate in Great Observatory-class missions, and thus to contribute to space science endeavours at a significant level. As a result, continuing the trajectory of JWST involvement by significant participation in Euclid/WFIRST has emerged as the LRP2010 panel's top space priority. However, it is important to note that Euclid/WFIRST is in an early planning phase, and final specifications for the

mission are not yet set. As noted in §5.1, if participation in Euclid/WFIRST is not possible, Canadian astronomers should explore the possibility of a Canadian-led UV/optical wide-field imaging satellite (CST) as a complement to Euclid/WFIRST.

It is important to emphasize that heavy investment in a single large international mission without appropriate support in other areas would result in an unbalanced program. The LRP2010 panel's recommendations are intended to map out an integrated and balanced plan for making the best use of Canada's new capability in space astrophysics, with ambitious and expensive international projects resting on a solid foundation of smaller missions. These smaller missions are exciting in their own right, and they provide essential core capabilities such as the training and R&D needed to develop and lead future large missions. For example, investments in missions and technological R&D related to precision metrology in this decade (e.g. Astro-H) will likely resonate in the next decade, enhancing Canada's prospects for contributing to missions such as IXO, which could well emerge as the top space-based priority for the next long range planning committee.

## 9.3 Outreach, Infrastructure, and Human Resources

| Category                                     | NSERC  | CSA                                    | CFI                         | CC       |
|--|--|--|-----------------------------|----------|
| <b>Outreach</b>                              | 1.5% of Astronomy new project funding (all agencies)   |  |                             | —        |
| <b>PDF's</b>                                 | 1. Project-oriented PDF support for ground-based astronomy \$700K/yr<br>2. 4 more CITA Fellows \$130K/yr | Mission-targeted PDF support \$300K/yr | —                           | —        |
| <b>University-based Instrumentation Labs</b> | Ground-based R&D \$1.5M/yr   | Space mission R&D \$750K/yr            | Instrument testbeds \$1M/yr | —        |
| <b>High Performance Computing</b>            | —  | —                                      | —                           | See note |

All amounts in the table refer to new funds.



## Explanatory notes:

### Outreach

See §8.3. Outreach is the cornerstone of all funding for pure research, and a basic responsibility for all involved; the LRPP urges all the agencies to find a way to return a portion of their investment to the taxpayers who fund our research. The LRPP also notes the important role that NRC-HIA plays in operating the Centre of the Universe (an outreach centre adjacent to the HIA telescopes), and AstroLab associated with OMM's facility.

### Project-oriented PDF support (NSERC)

See §7.3. The amount requested is the Astronomy component of the cancelled NSERC SRO program. Astronomy SRO's were primarily used for funding PDF's and research associates for specific projects, and this funding is urgently needed to make full use of the opportunities made available by existing and new facilities.

### Mission-targeted PDF Support (CSA)

See §7.3. The amount requested is obtained by scaling from NASA per orbit data reduction support for HST observations, and is equivalent to 4 PDF's. It will grow as other missions are launched.

### University-based Instrumentation Laboratories

The proposed budget for university-based experimental astrophysics laboratories assumes a network of three major centres across the country, each funded at the level of \$750K/yr for technical staff (engineers, technicians, research associates), relatively small R&D projects and operation cost. NSERC is targeted for approximately two-thirds of the cost and the remainder for CSA. This relative share between NSERC and CSA is provided only as an estimate and could vary from one centre to another depending

on the focus of their activities. The proposed CFI budget corresponds to an approximate envelope of \$10M (approximately \$3M per centre) integrated over a decade, for laboratory infrastructure (maintenance and upgrade of laboratory instrumentation) and relatively large R&D projects. The CFI budget does not include potential funding for new instruments and contributions to new facilities.

### High Performance Computing

In §3.4 we argue for a doubling of the Compute Canada budget for HPC. The new funds requested (\$30M/yr) are for all disciplines, not just astronomy. It should be noted that some of this funding is requested for personnel.

## 9.4 Concluding Remarks

### Importance of flexibility in the plan

Research in astronomy evolves rapidly: new ideas and discoveries can transition to facilities and programs on a timescale shorter than the decadal cadence of the LRP. Furthermore, the economic environment and funding landscape is exceptionally dynamic. As a result, LRP2010 is at best a "snapshot": it is simply not possible to anticipate all the needs of the community over a ten year horizon, and an element of flexibility must be built into the plan to accommodate new programs on small to intermediate scale. Such programs cannot be ranked against large projects such as a VLOT and the SKA; their success or failure must depend on rigorous peer review by the relevant agencies. Examples include SCUBA-2, which emerged shortly after the completion of the LRP2000 report; a proposed project that falls into this class is CHIME, and others will naturally emerge from a community as dynamic and vigorous as

ours. Though it is impossible for the LRP to track and rank all such projects, these initiatives may nevertheless be of high scientific merit and provide important training for HQP in fields of vital interest to Canadian astronomy.

### Recommendation 39

*It is important that Canadian funding agencies recognize the potential importance of astronomy projects of small to intermediate scale that develop on rapid timescales, 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.*

### LRP Implementation Committee (LRPIC)

The range of options and decisions facing LRP2010 is more complex than was the case for LRP2000. For example, at the time of writing, we cannot make an unqualified recommendation to commit to the TMT project, without further information on NSF funding and the construction timeline of the project (see §4.1.1). Whether or not we recommend that the CFHT telescope be replaced with a larger telescope depends on the outcome of VLOT funding in Canada (§4.2.4). Whether to pursue participation in one of the WFIRST or Euclid or CST Dark Energy satellites depends on factors that are rapidly evolving at CSA, NASA, and ESA (§5.1).

This complexity, coupled with the importance of flexibility in the LRP Plan discussed above, leads us to the following recommendation:

#### **Recommendation 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.*

This standing committee would be strongly focused on, and restricted to, monitoring and advising on developments relating to the LRP; this is not true of other existing committees. LRPIC should comprise a very small, highly experienced and skilled membership of the community to advise CASCA. The committee would meet as instructed by CASCA, and issue

a short annual report that could be made available to the agencies as well as the community. LRPIC is similar to a Mid-Term Review Committee, but operates on a continuous timeframe.

## **9.5 Summary of Recommendations**

The following is a summary of recommendations. These recommendations are numbered according to the ordering of material in the text, and not according to priority or ranking.

|          |  |
|----------|--|
| <b>1</b> | 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.   |
| <b>2</b> | The LRPP recommends that Canada's participation in Gemini be reconsidered as we reach the point that Canada's VLOT project requires operating funds.   |
| <b>3</b> | 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.   |
| <b>4</b> | 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 (descoped) SCUBA-2 surveys.   |
| <b>5</b> | 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.   |
| <b>6</b> | 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, in addition to continuing its existing programs that attract top researchers to Canada both in the short and long term, it can add 4 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.   |



|           |  |
|-----------|--|
| <b>16</b> | 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. |
| <b>17</b> | 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.  |
| <b>18</b> | 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).   |
| <b>19</b> | 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.   |
| <b>20</b> | The LRPP recommends that Canada develop the ngCFHT concept (science case, technical design, partnerships, timing).   |
| <b>21</b> | The LRPP recommends that a cost exercise be started immediately by CSA and Canadian astronomers to<br>(i) identify possible instrumentation contributions to space missions of interest, and<br>(ii) estimate the costs to Canada of these missions.   |
| <b>22</b> | 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<br>(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.  |
| <b>23</b> | The LRPP recommends Astro-H as its top priority small-scale space mission. The LRPP commends CSA for its rapid handling of this opportunity.   |

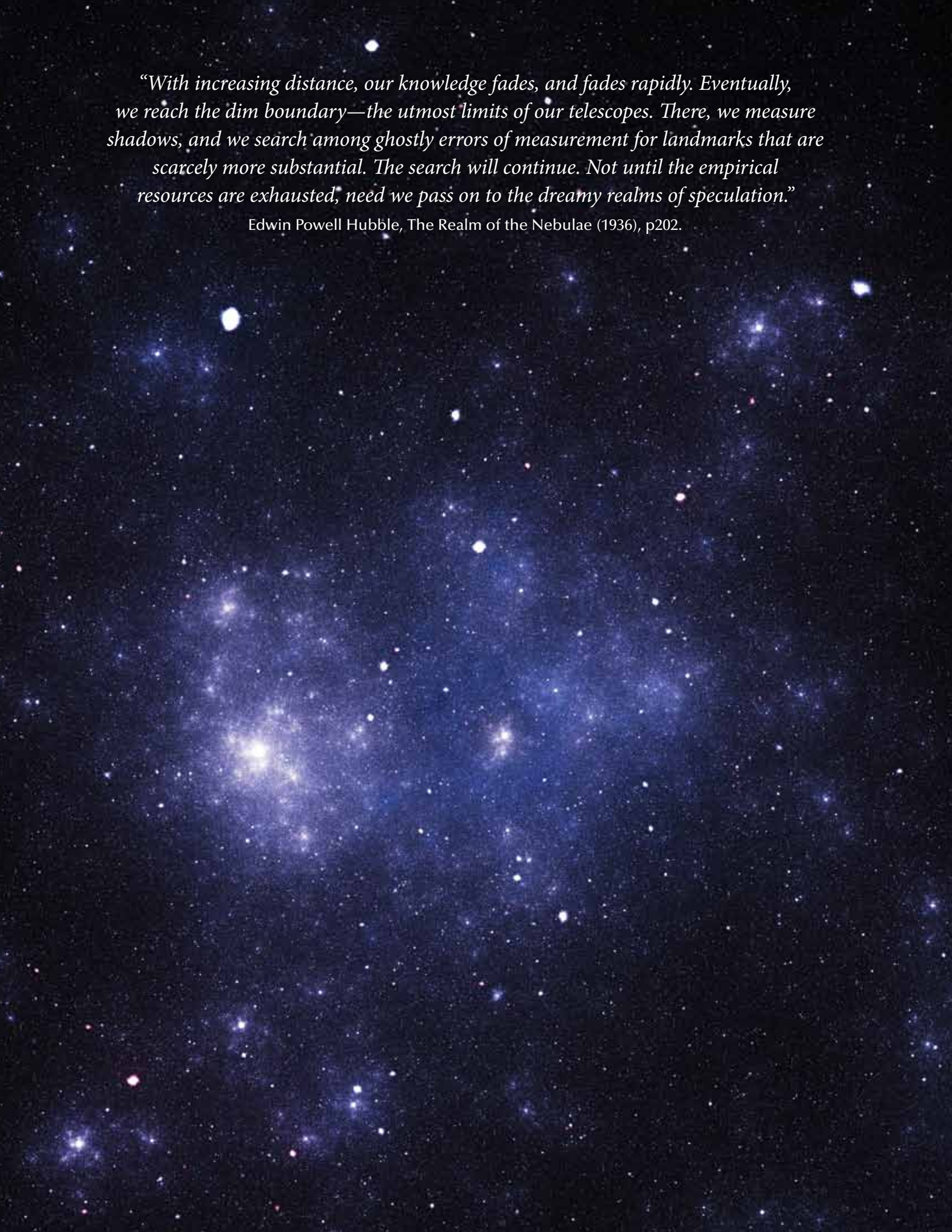
|    |  |
|----|--|
| 24 | The LRPP strongly recommends Canadian R&D involvement in IXO as its number 1 medium-scale space priority. This is because of its excellent foreseen scientific capabilities that will be a superb match for the expertise of the Canadian HEA community, but also with an eye toward 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 4 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.   |

|           |  |
|-----------|--|
| <b>35</b> | 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.   |
| <b>36</b> | Graduate programs should strongly consider adding some element of outreach, either training or project requirements, to their programs.  |
| <b>37</b> | The LRPP recommends that the "AstronomyCanada.ca" website be co-developed with a brand awareness campaign led by the professional community.   |
| <b>38</b> | The LRPP reiterates the value of investing a 1.5% fraction of government funding of new large-scale projects into outreach.  |
| <b>39</b> | It is important that Canadian funding agencies recognize the potential importance of astronomy projects of small to intermediate scale that develop on rapid timescales, 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. |
| <b>40</b> | 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.   |



*“With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search among ghostly errors of measurement for landmarks that are scarcely more substantial. The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation.”*

Edwin Powell Hubble, *The Realm of the Nebulae* (1936), p202.



## Appendices

### Appendix A – The Long Range Plan 2010

#### A.1 Terms of Reference<sup>20</sup>

##### *Context*

Astronomy and astrophysics play a significant role in our society, informing us about the nature of the Universe and our place within it. The development and funding of astronomical research in the 21st century is both a collaborative and competitive process. By identifying scientific, and hence funding, priorities in the 1999 Long Range Plan (hereafter LRP) the Canadian astronomical community has successfully facilitated the creation of the current generation of world class astronomical research and facilities. However, in the ten years since the previous plan, unanticipated avenues of research have opened up and a new generation of facilities are on the drawing board. These new developments need to be assessed and incorporated into an updated long range plan, LRP2010, that looks forward to the 2020 time frame.

The development of LRP2010 will be a collaborative process initiated by the Canadian Astronomical Society/Société canadienne d'astronomie (CASCA) with the support of all Canadian national agencies and organisations that fund or administer astronomical research. As with the original LRP, the initial review of the field and subsequent formulation of the LRP2010 will be undertaken by a primary Author Panel (hereafter the panel), led by a single Chairperson. Primary input is expected to come from the astronomical community through a series of subcommittees and open meetings.

The scope, structure, committee/panel membership, and community input processes for LRP2010 are described within this document.

##### *Statement of Task*

The panel will review the field of space and ground-based astronomy and astrophysics. Both current and future scientific goals and the various needs of the different Canadian communities in astronomy and astrophysics will be considered. From this review the author panel will then produce a list of recommended priorities for the next decade, to be outlined within LRP2010. These priorities will only include those considered to be essential to the success of the Canadian astronomical community. The resulting plan will serve as a single unified vision for highest priority projects in astronomy in Canada over the coming decade.

##### *Scope*

Formulation of LRP2010 is in outline a two-step process, namely a review followed by a prioritization exercise. It is anticipated that LRP2010 will address the following issues:

1. Assessment of the state of astronomy and astrophysics in Canada in the context of available astronomical facilities and the direct support of ongoing research programs. The review will consider all aspects of astronomy and astrophysics. Experimental and theoretical aspects of the field will be considered in tandem, with the consideration of the infrastructure that enables new discoveries being the primary task of the review. This review process will necessarily be in the context of the original LRP and will address both the successes and failures of the previous planning process.

2. Assessment of secondary infrastructure, including demographic issues, that are critical to the success of the Canadian astronomical community. While the primary evaluation task of LRP2010 is anticipated to encompass astronomical facilities, secondary infrastructure must also be considered. This includes, but is not limited to, facilities relevant to laboratory astrophysics, instrument design and development, storage and access of astronomical data, computer infrastructure used in the analysis and modelling of astronomical phenomena, and, importantly, the education and training of personnel. The success of our field is also dependent on ensuring equal access and representation. A review of the current demographics within the field will inform whether desired goals are being met. Considerations of these various aspects of the subject will then inform decisions on whether the appropriate infrastructure exists or needs to be developed to support future priorities.

3. Assess the state of our profession and its ability to take advantage of new opportunities. Set against the fundamental goal of maximizing future scientific advances, the review of our profession will directly inform the most beneficial and economic paths forward.

4. 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 the original LRP. The possibilities for new facilities will be assessed separately.

<sup>20</sup> Drafted by CASCA. See LRP2010 web page at <http://casca.ca/lrp2010>



5. 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 in either the original LRP or the mid-term review (MTR). Updating the LRP requires that we review these facilities/missions and assess their potential impact and possible benefits to the Canadian astronomical community. Understanding the possibilities for Canadian participation in major new international projects is anticipated to be a key component of this assessment. Given that Canadian researchers are also 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.

6. Formulate a prioritized list of facilities and programs that are essential to the success of the Canadian astronomical community. Building upon the previous assessments, 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. The panel may also choose to make recommendations for reorganization of research programs if current structures are deemed inappropriate for future endeavours. The decision on priorities will lie solely in the hands of the panel and is ultimately the most important aspect of LRP2010, setting the foundation for the highest priority projects in Canada over the coming decade.

7. Make budgetary recommendations for said facilities and programs and, where possible, suggest solutions to current funding challenges.

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. The suggested funding strategy will incorporate some measure of the relative risk associated with a given facility or program. In cases where funding is considered to be difficult, for whatever reason including such issues as inter-agency cooperation, the panel will make suggestions for possible resolutions. The final outcome of the review process is the production of an updated Long Range Plan for astronomy and astrophysics in Canada for the next decade. LRP2010 will be formulated in priority order within different categories to be decided upon by the author panel.

### *Approach*

Projects that were approved by the original LRP and MTR 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 must be incorporated within LRP2010. Throughout the process of determining 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 Conflicts of Interest) and will consult with independent authorities when necessary. It is critical to the overall success of the LRP that the assessment of science capability and budgetary demands is seen as a fair and rigorous process. The increasing overlap between fundamental physics and various areas of astronomy,

in particular cosmology, makes it difficult to consider these areas as distinct subjects. In situations where notable overlaps with other subject areas arise, the review will pay close attention to any goals that have been set in similar fields while still maintaining independence of process.

### *Selection of Chair of Author Panel*

The selection of the Chair is a critical issue since the LRP 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 and the agencies participating in LRP2010.

### *Selection Of Main Author Panel*

Once the Chair of the main 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 three or four panellists. 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 agency designates and the CASCA Board.

### *Structure of Review: Working Groups*

The original LRP and MTR relied upon CASCA committees to provide reports to the author panel. The author panel will decide on the sub-committee structure to be used in LRP2010.



## A.2 LRP Panel Members

|                        |                |                 |                            |
|------------------------|----------------|-----------------|----------------------------|
| <b>Roberto Abraham</b> | U. Toronto     |                 | abraham@astro.utoronto.ca  |
| <b>René Doyon</b>      | U. de Montréal |                 | doyon@astro.umontreal.ca   |
| <b>Nick Kaiser</b>     | U. Hawaii      |                 | kaiser@ifa.hawaii.edu      |
| <b>Vicky Kaspi</b>     | McGill U.      |                 | kaspi@physics.mcgill.ca    |
| <b>Chris Pritchett</b> | U. Victoria    | Chair           | pritchett@uvic.ca          |
| <b>Ernie Seaquist</b>  | U. Toronto     | Resource Member | seaquist@astro.utoronto.ca |
| <b>Rob Thacker</b>     | St. Mary's U.  | Vice-Chair      | thacker@ap.smu.ca          |

### *Deliverables*

The author panel will deliver the final version LRP2010 (in English) and associated recommendations to the President of CASCA. The LRP will then be simultaneously released, in both official languages, to all relevant parties including NSERC, the NRC, CFI, CSA and relevant Ministries of the Government of Canada.

### *Schedule*

The review process will begin upon appointment of the Chair of the author panel, which is anticipated to be announced at the CASCA 2009 meeting. 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 launch of LRP2010 in Fall 2010.

### *Conflicts of Interest*

The members of all committees will ensure that all work conducted under the auspices of said committees is conducted in a manner free of conflicts of interest. Any persons associated with the committees are also bound to similar conduct. For the purposes of this review, a conflict of interest is defined to be a

situation where any committee member or his/her family is able to benefit financially from involvement in the review process, or if a prioritized 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. It may be necessary to exclude a panel member from participation in debate about a particular project priority. Committee members are also advised to provide early notification of the possibility of conflicts occurring.

### *Confidentiality*

The review is expected to be an accountable and open process. Submissions to the project will be made public however proprietary information may be so-indicated and will be kept confidential. However, prior to mutually agreed upon release dates, all committee members are to agree that they will not disclose or give to any person any information or documents relating to LRP2010.

## A.3 LRP2010 Activities

The LRP Panel was commissioned by CASCA, with the co-operation of ACURA, NSERC, NRC, CSA, and CFI. The LRPP was formed and approved

by CASCA and the agencies during the months of September and October 2009. Funding for committee activities was negotiated during these months, with contributions from ACURA, NSERC, NRC and CSA; a final budget was approved in November 2009.

The first meeting of the LRPP was held at McGill U, Montréal on Nov 19, 2009. This meeting was followed by an information-gathering process; the resultant white papers can be found online<sup>21</sup>. A meeting of the LRPP to evaluate the white papers was held at U. Toronto on Feb 26.

A series of Town Hall Meetings was held in March 2010 (U. Calgary, Mar 9; HIA, Victoria, Mar 10; U. de Montréal, Mar 16; U. Toronto, Mar 17). The LRPP met to consider the Town Hall meetings and white papers on Apr 29-30 at CSA headquarters and at McGill U., Montréal. A final community Town Hall meeting was held May 26, 2010 at the CASCA meeting (St. Mary's U., Halifax).

The writing of draft sections of the document took place over the summer, followed by a meeting to consider the drafts Sep 27-28, 2010. The document was assembled and edited over the following two months.

<sup>21</sup> <http://casca.ca/lrp2010/Docs/LRPReports/WhitePaperList.html>

## Appendix B – Funding Details

### Summary of Funding – All Agencies

The following table summarizes annual funding over the past 20 years for a number of different agencies and institutes. A figure comparing these data can be found in §6.1, with some interpretation. Note that the NRC-HIA component does not include salaries.

| Year                 | NRC-HIA         | NSERC           | CSA             | CFI            | CIFAR          |
|----------------------|-----------------|-----------------|-----------------|----------------|----------------|
| 1991 – 1992          | 9.015           | 5.276           | –               | –              | 0.597          |
| 1992 – 1993          | 13.225          | 5.609           | –               | –              | 0.706          |
| 1993 – 1994          | 14.690          | 7.835           | –               | –              | 0.888          |
| 1994 – 1995          | 17.837          | 5.537           | –               | –              | 0.757          |
| 1995 – 1996          | 11.747          | 5.210           | –               | –              | 0.768          |
| 1996 – 1997          | 13.382          | 10.792          | –               | –              | 0.680          |
| 1997 – 1998          | 12.256          | 5.824           | –               | –              | 0.646          |
| 1998 – 1999          | 12.253          | 5.824           | –               | 0.189          | 0.688          |
| 1999 – 2000          | 15.959          | 6.262           | 5.2             | 1.880          | 1.074          |
| 2000 – 2001          | 21.104          | 6.476           | 4.9             | 1.162          | 1.172          |
| 2001 – 2002          | 20.206          | 7.565           | 6.5             | 0.542          | 1.098          |
| 2002 – 2003          | 19.518          | 8.528           | 6.9             | 21.006         | 0.935          |
| 2003 – 2004          | 17.828          | 10.028          | 8.9             | 1.423          | 0.867          |
| 2004 – 2005          | 18.828          | 10.170          | 12.7            | 4.077          | 1.021          |
| 2005 – 2006          | 17.418          | 11.242          | 18.3            | 0.713          | 1.201          |
| 2006 – 2007          | 21.699          | 11.684          | 29.1            | 2.909          | 1.350          |
| 2007 – 2008          | 21.803          | 12.202          | 37.9            | 0.713          | 1.039          |
| 2008 – 2009          | 21.375          | 12.506          | 41.5            | 0.475          | 1.022          |
| 2009 – 2010          | 22.735          | 11.798          | 36.1            | 0.187          | 1.155          |
| <b>Total 2000-10</b> | <b>\$202.5M</b> | <b>\$102.2M</b> | <b>\$202.8M</b> | <b>\$33.2M</b> | <b>\$10.9M</b> |

Notes: All amounts are in millions of dollars per year. Funding for CFI is from year start to year end; other numbers are for fiscal years. None of these amounts is adjusted for inflation.

NRC-HIA: funding excludes salaries and benefits. See below for further details.

CSA: Information is unavailable prior to 1999.

NSERC: funding includes all astronomy support including scholarships and fellowships. Total 2000-2010 assumes \$8M for 2009-2010. See below for further details, including statistics on Discovery Grants.

CIFAR: Cosmology and Gravitation Program only.

NSERC and CFI numbers are from their web-based search engines. We acknowledge the assistance of Dr. Greg Fahlman (NRC-HIA), Dr. Denis Laurin (CSA), and Elizabeth Gerrits (CIFAR) in collating information for the other agencies.

## NRC-HIA Funding Details

| FY        | Salaries+<br>Benefits | O&M    | Total<br>Ops | Capital | Offshore | Total  |
|-----------|-----------------------|--------|--------------|---------|----------|--------|
| 1991-1992 | 10.493                | 2.769  | 13.262       | 1.315   | 4.931    | 19.508 |
| 1992-1993 | 11.428                | 3.044  | 14.472       | 1.069   | 9.112    | 24.653 |
| 1993-1994 | 12.206                | 2.973  | 15.179       | 1.052   | 10.665   | 26.896 |
| 1994-1995 | 11.690                | 2.882  | 14.572       | 0.816   | 14.139   | 29.527 |
| 1995-1996 | 10.685                | 2.626  | 13.311       | 0.741   | 8.380    | 22.432 |
| 1996-1997 | 7.476                 | 2.939  | 10.415       | 0.598   | 9.845    | 20.858 |
| 1997-1998 | 7.145                 | 3.037  | 10.182       | 1.058   | 8.161    | 19.401 |
| 1998-1999 | 7.576                 | 3.101  | 10.677       | 1.470   | 7.682    | 19.829 |
| 1999-2000 | 7.559                 | 4.108  | 11.667       | 3.371   | 8.480    | 23.518 |
| 2000-2001 | 7.834                 | 4.186  | 12.020       | 6.317   | 10.601   | 28.938 |
| 2001-2002 | 8.695                 | 4.810  | 13.505       | 4.795   | 10.601   | 28.901 |
| 2002-2003 | 10.165                | 5.803  | 15.968       | 3.269   | 10.446   | 29.683 |
| 2003-2004 | 12.432                | 6.196  | 18.628       | 1.511   | 10.121   | 30.260 |
| 2004-2005 | 12.727                | 7.638  | 20.365       | 0.421   | 10.769   | 31.555 |
| 2005-2006 | 13.308                | 6.970  | 20.278       | 1.023   | 9.425    | 30.726 |
| 2006-2007 | 13.289                | 7.320  | 20.609       | 1.810   | 12.569   | 34.988 |
| 2007-2008 | 13.998                | 12.199 | 26.197       | 0.416   | 9.188    | 35.801 |
| 2008-2009 | 14.633                | 10.146 | 24.779       | 0.710   | 10.519   | 36.008 |
| 2009-2010 | 16.841                | 11.552 | 28.393       | 0.503   | 10.680   | 39.576 |

Notes: Funds are in millions of dollars. Total Operating is the sum of Salaries plus Benefits, and Operations and Maintenance. Offshore refers to offshore facilities. The total is the sum of columns 4 to 6.

Offshore facilities vary considerably because of exchange rate fluctuations.

The “spike” in capital funding 1999-2003 is because of the construction of new HIA buildings in Victoria (DAO) and Penticton (DRAO).



## NSERC Funding Details

Figure A-1 and the Table below show a more detailed view of NSERC funding. The lower blue curve is individual Discovery Grant funding. (There are very few team grants in the discipline.) The middle red curve shows the total research funding support available to faculty; this includes DG's, MRS grants etc. The black curve shows the total support in all categories, including CRC Chairs, postgraduate fellowships, undergraduate awards, etc. The top panel shows the average individual DG. Inflation has not been corrected in these plots. This figure is discussed in Sections 6.1 and 6.4.1.

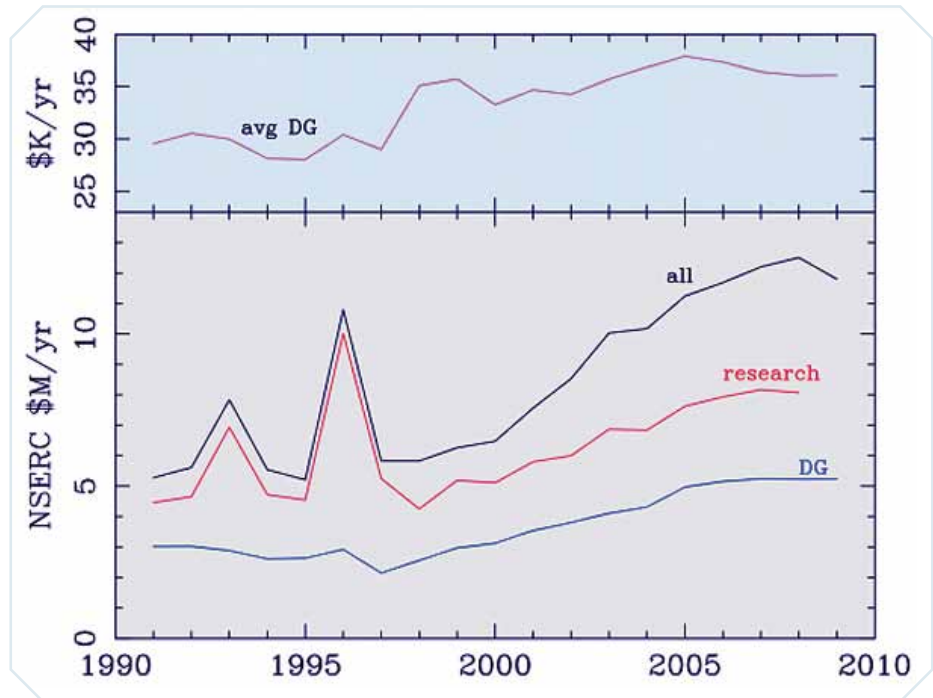


Figure A-1. (Lower panel) Total NSERC funding per year for astronomy and astrophysics. Black line: all funding; red line: research funding, excluding scholarships, fellowships, undergraduate awards, CRC chairs; blue line: individual Discovery grants. (Upper panel) Average NSERC individual Discovery Grant. See text for details.

| Year      | # DGs | Avg DG (\$) | Total DG (\$M) | Total Research (\$M) | Total (\$M) |
|-----------|-------|-------------|----------------|----------------------|-------------|
| 1991-1992 | 102   | 29555       | 3.015          | 4.284                | 5.276       |
| 1992-1993 | 99    | 30529       | 3.022          | 4.527                | 5.609       |
| 1993-1994 | 96    | 29977       | 2.878          | 6.834                | 7.835       |
| 1994-1995 | 93    | 28135       | 2.617          | 4.616                | 5.537       |
| 1995-1996 | 94    | 28034       | 2.635          | 4.440                | 5.210       |
| 1996-1997 | 96    | 30399       | 2.918          | 10.013               | 10.79       |
| 1997-1998 | 74    | 28993       | 2.146          | 5.185                | 5.824       |
| 1998-1999 | 73    | 35102       | 2.562          | 4.183                | 5.824       |
| 1999-2000 | 83    | 35749       | 2.967          | 5.156                | 6.262       |
| 2000-2001 | 94    | 33276       | 3.128          | 5.108                | 6.476       |
| 2001-2002 | 102   | 34694       | 3.539          | 5.797                | 7.565       |
| 2002-2003 | 111   | 34261       | 3.803          | 5.998                | 8.528       |
| 2003-2004 | 115   | 35722       | 4.108          | 6.750                | 10.028      |
| 2004-2005 | 117   | 36872       | 4.314          | 6.721                | 10.170      |
| 2005-2006 | 131   | 37917       | 4.967          | 7.624                | 11.242      |
| 2006-2007 | 138   | 37363       | 5.156          | 7.933                | 11.684      |
| 2007-2008 | 144   | 36420       | 5.244          | 8.313                | 12.202      |
| 2008-2009 | 145   | 36055       | 5.228          | 8.218                | 12.506      |
| 2009-2010 | 145   | 36095       | 5.234          | 7.207                | 11.798      |

## CSA Funding

We are grateful to Dr. Denis Laurin and Sebastien Bourgeois for the following detailed breakdown of CSA funding to Astronomy. All amounts are in \$M, without correction for inflation.

| Mission / Activity | Launch Year | FY 99      | FY 00      | FY 01      | FY 02      | FY 03      | FY 04       | FY 05       | FY 06       | FY 07       | FY 08       | FY 09       | TOTAL (\$M)  |
|--------------------|-------------|------------|------------|------------|------------|------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|
| VLBI (VSOP)        | 1997        | 0.5        | 0.3        | 0.4        | 0.4        | 0.2        |             |             |             |             |             |             | 1.8          |
| FUSE (FES)         | 1999        | 0.7        | 0.5        | 0.5        | 0.4        | 0.3        | 0.3         | 0.2         | 0.1         |             |             |             | 3.0          |
| ODIN (OSIRIS)      | 2001        | 0.7        | 0.9        | 0.7        | 0.8        | 0.4        | 0.3         | 0.6         | 0.3         | 0.3         | 0.3         | 0.3         | 5.5          |
| MOST               | 2003        | 1.5        | 1.9        | 2.5        | 2.3        | 1.9        | 1.0         | 1.0         | 1.0         | 0.8         | 1.0         | 0.7         | 15.6         |
| BLAST              | 2005        |            |            | 0.2        | 0.2        | 0.2        | 0.3         | 0.2         | 0.3         | 0.3         |             |             | 1.8          |
| Herschel/Planck    | 2009        | 0.4        | 0.4        | 0.9        | 1.9        | 2.9        | 4.3         | 4.7         | 1.9         | 1.4         | 1.4         | 1.3         | 21.4         |
| Astrosat (UVIT)    | 2011        | 0.0        | 0.0        | 0.0        | 0.0        | 0.0        | 0.5         | 1.6         | 1.5         | 1.0         | 1.2         | 1.3         | 7.2          |
| EBEX               | 2009        |            |            |            |            |            |             |             |             |             | 0.2         | 0.5         | 0.7          |
| NEOSSAT            | 2011        |            |            |            |            |            | 0.2         | 0.3         | 0.3         | 2.3         | 1.1         | 2.4         | 6.6          |
| JWST (FGS, TFI)    | 2015        |            |            |            |            | 0.2        | 3.9         | 8.6         | 22.8        | 30.9        | 34.7        | 28.7        | 129.9        |
| NGST (pre-JWST)    |             | 1.0        | 0.5        | 0.8        | 1.0        | 1.9        | 1.0         | 0.0         | 0.0         | 0.0         | 0.0         | 0.0         | 6.2          |
| CADC / HST         |             | 0.3        | 0.2        | 0.2        |            | 0.4        | 0.3         | 0.4         | 0.4         | 0.2         | 0.2         | 0.2         | 2.8          |
| Other              |             | 0.2        | 0.2        | 0.4        | 0.0        | 0.4        | 0.5         | 0.5         | 0.6         | 0.7         | 1.2         | 0.6         | 5.4          |
| <b>TOTAL</b>       |             | <b>5.2</b> | <b>4.9</b> | <b>6.5</b> | <b>6.9</b> | <b>8.9</b> | <b>12.7</b> | <b>18.3</b> | <b>29.1</b> | <b>37.9</b> | <b>41.5</b> | <b>36.1</b> | <b>207.9</b> |

### NOTES:

- Figures are approximate; due to rounding, figures may not add up to totals shown.
- Amounts for early part of decade do not always include full-cost accounting.
- Amounts are not adjusted for inflation.
- MOST, UVIT, Herschel, Planck, JWST, Astrosat include scientific support.
- NEOSSat is jointly funded by DRDC and CSA. Figures above show only CSA funding, and not under “Astronomy”.
- ODIN is split with Atmospheric Sciences.
- Information for pre-1999 not available at this time.
- Missions such as VLBI, FUSE, ODIN do not show full mission costs, but rather operation costs for that period.



## Appendix C – Student Training

### Demographics and trends: overall population

Demographic analysis, summarized in Figure A-2, shows that since 2000, there has been significant and steady growth in student involvement in research astronomy. At the graduate level, the 1999 ACURA survey of astronomy departments shows 159 graduate students across Canada, while by 2009 this had risen to 296, almost a doubling of the

population. It is worth noting that student numbers, and their growth, depend inexorably on NSERC funding through Discovery Grants and Scholarships.

Perhaps more remarkably, the number of undergraduates involved in research has grown from 63 in 1999 to 165 by 2010, which corresponds to an annual growth rate of 10% over the ten-year period. However, most of the increase in undergraduate numbers happened prior to 2007, while the graduate enrolment increase is reasonably steady at 6% per year in the ten year period.

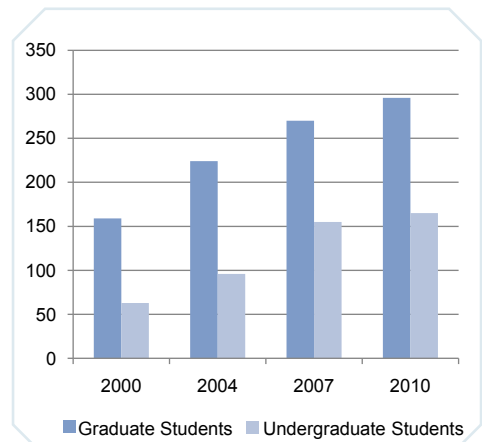


Figure A-2. Growth in the number of graduate and undergraduate students involved in astronomy research in Canada over time.

### Demographics and trends: PhD outcomes

The LRPP initiated a survey of all post-1990 PhDs in Canada through the Dept. Chairs of PhD granting institutions. While responses were not complete, the ten highest ranked departments in Canada as measured by total NSERC Discovery Grants all provided data. A total of 257 records were analyzed; we view this as a representative sample.

In Figure A-3 we plot the number of PhDs awarded per year. The overall growth shown in this graph is slightly below the annual growth rate of 6% for total graduate enrollment, but we emphasize that these numbers are for PhDs alone. The field is granting approximately one additional PhD every two years. Some years stand out, most notably 2009, in which 27 PhDs were granted (equal to the entire total for 1990-1994). Canadian astronomy is clearly making immense strides in the successful training of a cadre of new astronomers.

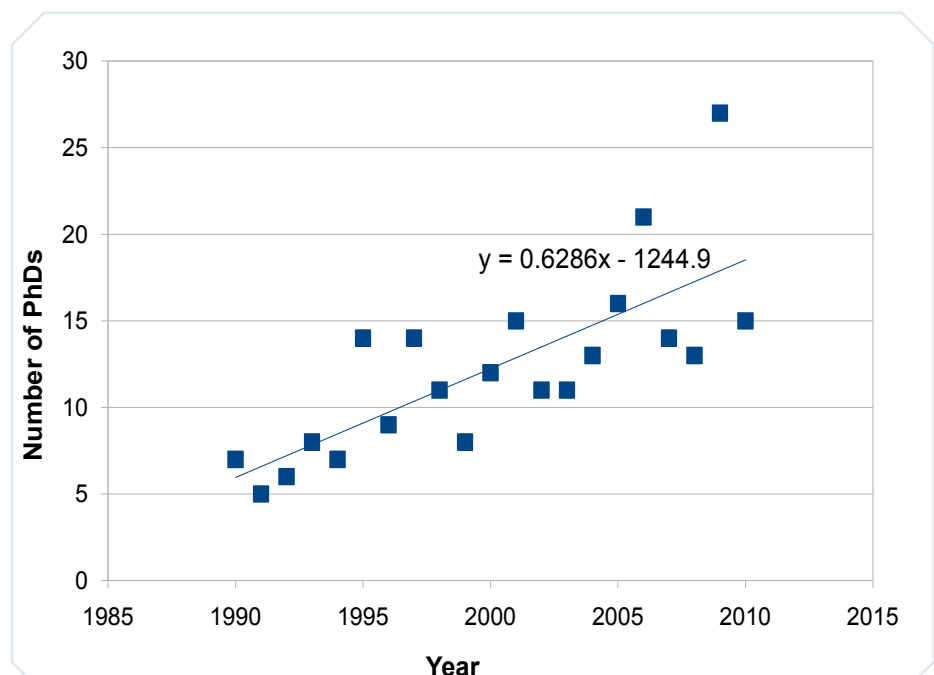


Figure A-3. PhD graduates in Canadian astronomy as a function of year, with a best fit.

## Post-PhD employment

There is nonetheless an imbalance between the number of PhDs granted and the number of available positions in the astronomy field. It is therefore critical to examine where PhD graduates find employment. Of the 257 records, employment data was provided for 95%. We again consider this a representative sample.

We consider four distinct streams of employment: industry/teaching (including the financial sector, software development, high school teaching and the medical field); research/lecturing, which contains those individuals employed at research institutes, including staff astronomers at observatories and also part-time lecturing positions at universities; tenure-track faculty, which includes universities, colleges, CEGEPs, and permanent positions at HIA and CSA; and PDF positions.

The data are displayed in pie chart format in Figure A-4. Approximately 1 in 5 graduates transition into industry/teaching, and a similar number find employment in tenure track positions. The largest single employment category is PDF positions, in which 1 in 3 PhD graduates can be found. We note that PDF positions are temporary, and the increasing number of recent graduates, in particular the 27 in 2009 alone, may be systematically biasing numbers toward the PDF category. Next largest is the research/lecturing category, in which 1 in 4 graduates find employment. The bulk of these positions are at research institutes.

Of the 43 records in the industry/teaching category we can further subdivide into industry, teaching, computing, finance, medical and government employment. These data are shown in Figure A-5. Both the financial sector and software development continue to be strong employers of PhD astronomers. This is no surprise given

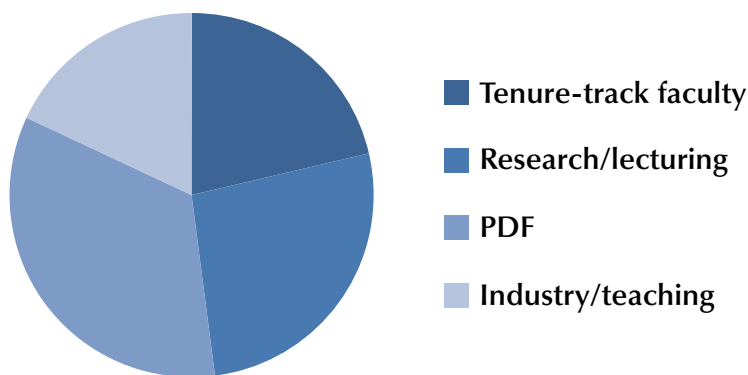


Figure A-4. Current employment by area for PhD graduates in astronomy in the 2000-2010 decade.

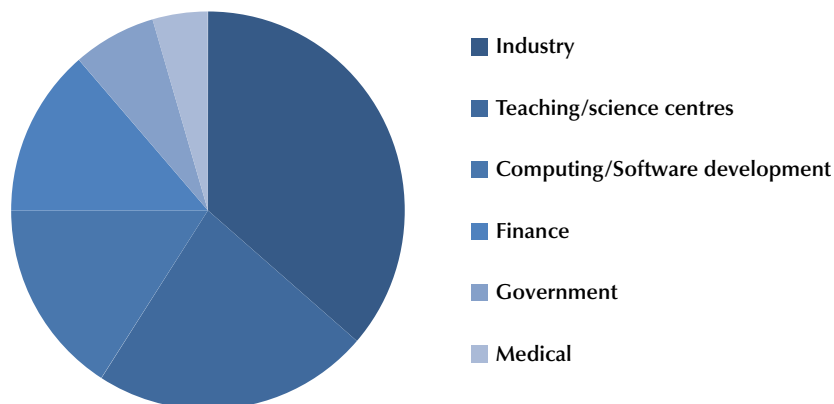


Figure A-5. Subdivision of the industry/teaching category.

the level computing skill and mathematical literacy developed as part of a PhD degree.

## Male/female ratio

As some institutions only provided anonymous data records, the participation of women in PhD programs is difficult to assess. However, at 70% completeness (183 records) we find that 1 of 5 PhDs is female averaged over two decades. This ratio increased markedly over time, from 12% in the 1990-1999 period to 24% in

the last decade (2000-2009). This growth is consistent with the current male/female ratio in the student membership of the Canadian Astronomical Society. The 2010 student membership category lists 174 members, corresponding to a membership rate of roughly 60% relative to the total graduate population as measured by the ACURA survey. Of these records we find that 46% are female, a figure remarkably close to parity. The fraction of female PhDs is likely to continue its growth in this decade.

## Student Nationality

In addition to the student outcomes, the survey allowed the LRPP to examine the number of foreign students pursuing astronomy PhDs in Canada. Nationality data were provided at almost 80% completeness; approximately 1 in 6 PhDs in astronomy are granted to non-Canadians. Many graduate coordinators have commented that a large number of PhD applicants are received from outside the country, but budgetary considerations mean many of these applicants must be turned away, regardless of quality.

## Subject area

Dividing PhD area coarsely between theory and observation shows that approximately 2/3rd of the PhDs are in observational astronomy. This is in approximate agreement with the split in specialization of faculty across the country, which we estimated using the membership of CITA Inc.

## Industrial Training Opportunities

Astronomers have a broad and unique training regimen that is highly praised within Canadian industry. Integrated over the past two decades, 7% of PhDs ended in industry. The last decade has seen a number of PhD students trained partly within industry on projects related to experimental astrophysics. One of these PhDs was awarded the Plaskett medal (best thesis in astronomy/astrophysics in Canada) in 2006. With the increase in faculty working in close collaboration with industry, student involvement with industry is expected to grow significantly over the next decade.

## Appendix D – Postdoctoral Fellows

### Demographics and trends

Demographic analysis, summarized in Figure 7-1, shows that since 2000, there has been significant and steady growth in the postdoctoral positions in Canada. In 1999 the ACURA survey of astronomy departments showed 44 postdoctoral positions across Canada, while by 2009 this had risen to 108.

This amounts to 9% growth per year over the period, and closely matches the reported doubling of postdoctoral positions observed in the US over the same decade. In the same time period there was 5% growth per year in the number of faculty positions, and a 6% growth per year in the number of graduate students. With the total population in all these sectors (including adjunct professors) being slightly under 600, PDFs account for less than 1/6th of professional population.

These averaged decadal statistics do not reveal some important facts. Firstly, by far the largest growth in PDF numbers occurred in the period 2000-2004. A significant injection of funding saw PDFs

numbers almost double (from 44 to 80). Since 2004 PDF numbers have grown at 5%, in keeping with faculty and graduate student numbers. Also 60% of the current postdoctoral population resides at four institutions, University of Toronto, University of British Columbia, University of Victoria and McGill University. It is important to note that while the fraction of national faculty at these institutions has remained at 35% since 1999, at that time these institutions had a 15% lower share of the PDF population. Since 2004, growth in the PDF population at other institutions averages 1.5% per year.

We thus have two distinct periods of growth: 2000-2004, when growth was rapid and achieved across the board; and 2004-2010, when growth was largely centred at four institutions.

To further understand the funding situation, the LRPP conducted a survey of funding mechanisms for PDFs. The survey includes data for over 4/5 of the current PDF population in Canada, and is shown in Figure A-6. Note that this survey only includes funding sources, and not the relative amount from each source. The ubiquity of using NSERC DG funds to top up PDFs may mean that the actual

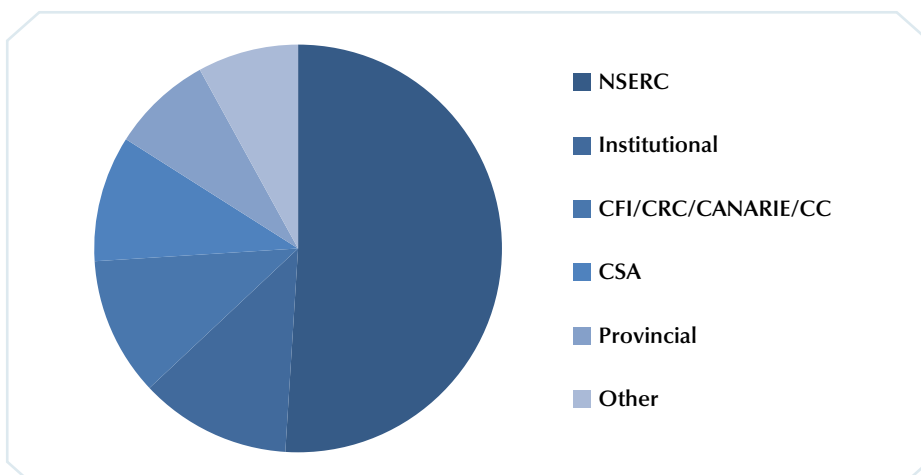


Figure A-6. Fractional funding of PDFs in Canada by source.



monetary contribution of NSERC is somewhat overestimated in these figures. Nonetheless, NSERC is the single highest contributor to PDF funding, providing 51% of the PDFs identified in this survey. Institutional funding, including grants from university-administered foundations, was the second highest supporter of PDFs at 12%. CRC, CFI, CANARIE and Compute Canada funds contribute to 11% of PDFs. The CSA contributes 10% and provincial funding 8%. CANARIE and Compute Canada represent a new funding source that was not available at the time of LRP2000, similarly a fraction of provincial and CFI/CRC funds can be viewed as being new sources of PDF funding in the last decade.

## Growth in Context

An almost universal call for more PDFs appeared in white papers and was voiced during town hall meetings. The primary driver behind these requests appears to be the community's success in obtaining observing time in the international time allocation process, and anticipated manpower needs for upcoming observatories like ALMA and JWST. A similar argument was made for more theory-oriented PDFs, where an increase in multi-physics simulation is requiring more effort in development time. Given

that the demographic analysis shows 65% of the faculty in Canada have not had any appreciable new sources of funding for PDFs since 2004, the requests for additional funding appear warranted.

It is important to compare Canada with comparable international data. Does Canada have a proportionally lower PDF to faculty ratio than other countries? The LRPP conducted an informal survey of institutions across both the US and Europe, including both specialist research oriented universities and larger state schools. Research institutes that would likely bias the PDF to faculty ratio higher were not included. The results were as follows: for 204 faculty (larger than the entire astronomy faculty in Canada) there were 212 PDFs, close to a 1-to-1 ratio. Within Canada, the total number of astronomy faculty is 200, while the number of PDFs is 108, giving a ratio of  $\frac{1}{2}$ . Canada does indeed appear to have a deficit of PDFs compared to international averages.

## Appendix E – International funding

Deriving spending figures on astronomy is non-trivial. Some countries, especially Germany, have an extremely complicated

funding structure that makes it difficult to assess the overall spending. The US is equally difficult to determine because of the role of the substantial private investment in astronomy. Others, such as the UK, have a single funding council, thus making the process straightforward. The comparisons below should be treated with caution and an error margin of 20% is likely a good rule of thumb.

In the following analysis we have attempted to present as conservative an assessment as possible, meaning that we have *maximized* Canadian investment while presenting *minimum* numbers for other countries. Specifically, the 2009 investment in Canadian astronomy includes an exceptional contribution from the CSA due to JWST development. For comparison, the 2009 budget of \$36.1M for space astronomy is over 7 times higher than \$4.9M budget of FY2000, at the time of the last LRP.

We therefore strongly emphasize that the derived ratios are lower bounds on the difference in spending between Canada and other countries. Comparisons using 2006 data would show the gap between Canadian expenditure and other countries to be significantly larger.

In the following table, GDP (2010) estimates are from the International

| Country   | Ground-based<br>[\$CAD M] | Space-based<br>[\$CAD M] | Total<br>[\$CAD M] | GDP<br>[\$CAD M] | Spending/GDP<br>As % | Relative<br>to Canada |
|-----------|---------------------------|--------------------------|--------------------|------------------|----------------------|-----------------------|
| UK        | 170                       | 165                      | 335                | 2222000          | 0.015                | 2.7                   |
| ITALY     | 255                       | 55                       | 310                | 2121000          | 0.015                | 2.6                   |
| FRANCE    | 248                       | 84                       | 332                | 2688000          | 0.012                | 2.2                   |
| GERMANY   | 327                       | 69                       | 396                | 3332000          | 0.012                | 2.1                   |
| USA       | 550                       | 1103                     | 1653               | 14799000         | 0.011                | 2.0                   |
| AUSTRALIA | 79                        | 13                       | 92                 | 1192000          | 0.008                | 1.4                   |
| CANADA    | 51                        | 36                       | 87                 | 1556000          | 0.006                | 1.0                   |

Monetary Fund. Given the historically low inflation measures from 2008 to 2010, we have not attempted to adjust for relative changes in monetary value except for the German figures that are quoted in the source in Y2000 Euros. Exchange rates assumptions are, US\$ to CAD\$ 1.0, Euro to CAD\$ 1.38, pound to CAD\$ 1.61, AUS\$ to CAD\$ 1.0.

Below we summarize the sources of astronomy spending numbers and an assessment of the veracity of the data.

## UK

STFC 2010-11 budget. These numbers are the best direct comparison to another country and cleanly allow a separation of ground-based and space-based spending. The ESA payment is especially large due to the additional inclusion of support for the ESA AURORA program.

## USA

FY2010 budgets for NASA astrophysics and the NSF AST budget plus MREFCs for ALMA and AdvLIGO. We have not added the NASA heliophysics budget which would increase numbers by a further \$600M. We have also followed the LRP2000 process of adding a component of private funding to account for the vast impact these sources have on ground-based US funding. We have thus scaled the FY2000 of \$76M to \$100M according to inflation across the decade. We also include Department of Energy non-accelerator funding and Department of Defense related spending. These are estimated by the AAS to be 10% of the overall US astronomy budget. We have therefore added a conservative 100M to the ground-based numbers. Space-based and ground-based numbers were separated by breaking out the NASA budget. Other than the DoE, DoD and private estimates, these numbers can be considered accurate.

## France

Numbers were derived from the “*Report on the Management of European Astronomy*” a document prepared for the ASTRONET planning process in 2007. We subtracted the 58M Euro staff costs associated with both national labs and universities. Space-based figures correspond to the ESA space science payment (61M Euro) included in this assessment. We note this is an extremely small fraction of the overall French spending on ESA. Our figure overall figure of 241M Euro compares to an estimate of 240M Euro published in “*Europe’s Quest for the Universe*” (2006) by Lodewijk Woltjer (former Director General of ESO). The agreement between the two sources suggests the numbers are accurate.

## Germany

Numbers were again derived from the “*Report on the Management of European Astronomy*”. The overall figure of 226M Euro (in Y2000 Euros) when converted to 2010 Euros (287M) is extremely close to the 285M Euro estimated by Woltjer in 2006.

## Italy

Spending was taken from the estimate in “*Europe’s Quest for the Universe*” (2006) by Lodewijk Woltjer. Although Italy is discussed in the ASTRONET document, funding figures are not presented in a summary form. Based upon the accuracy of Woltjer’s numbers for Germany and France, these numbers are likely accurate overall, although the estimated ESA payment of 40M Euros might be an underestimate.

## Australia

Numbers were taken from the Australian Telescope National Facility annual report for 2009, the Anglo Australian Observatory

operational budget, annual Gemini subscription, plus contributions to the equipment program, the 2009 Super Science “Space Science” funding, the Pawsey SKA centre funding (\$80M over 4 years averaged to \$20M for one year) and the National Collaborative Grants Program estimated to be \$13M (2005 funding level plus the additional \$3M per year to CAASTRO). With the exception of the NCGP funding these numbers can be considered accurate. Funding provided by NCRIS and administered by Astronomy Australia limited is difficult to track but likely adds only a few million, and we have not included it.

## Canada

Numbers were taken from Appendix B in this document.

## Appendix F – Examples of Industry-Astronomy Success Stories

In this appendix to §8.2 we present some examples of Canadian companies (east to west) that have benefited in a demonstrable way from contracts in astronomy projects. Additional examples may be found in the LRP2000 report.

### ABB Bomem – Québec, PQ

ABB Bomem is one of the largest Canadian-based designers and manufacturers of space hardware subsystems. The company has been involved with space and ground astronomy instrumentation projects for over 15 years. The company has expertise in optical and infrared instrumentation and metrology systems. Contributions to astronomy projects include the SpIOMM imaging spectrometer instrument operating at Mégantic

Telescope in Quebec, the optical ground support equipment to optically calibrate the Fine Guidance Sensor (FGS – a Canadian contribution to the JWST), the Sitelle instrument for the CFHT, and metrology systems for future space-based observatories. ABB promotes strategic involvement with academic sector, through involvement with research chair or CFI grants (U. Laval, U. de Montréal, and York). Overall, astronomy contracts since 1997 are valued at \$4M USD. More importantly, they have helped ABB to promote themselves favourably in developing space instrumentation unrelated to astronomy, leading to contracts valued at \$100M over 10 years.

## Lyrtech Signal Processing – Québec City, Québec

Lyrtech is a Canadian company based in Québec City with approximately 70 employees, including about 40 engineers and researchers. They are leading design house and original design manufacturer that develops advanced digital signal-processing (DSP) solutions involving IP, components, firmware, software and systems, as standard or custom products.

Lyrtech supplied the DSP system for HIA's PHased Array feed Demonstrator (PHAD) – a new type of smart antenna. The DSP system for PHAD was much larger than Lyrtech had ever supplied and it permitted PHAD to be the first to demonstrate the feasibility of multi-beam polarization measurements on a radio-telescope. Such results helped Lyrtech in its marketing and sales efforts. More importantly such systems are becoming more pervasive and have applications to radar, surveillance, monitoring and wireless communications.

Another important new area is FPGA computing. Using Field Programmable Gate Arrays (FPGAs) custom compute engines can be made that are tailored for an algorithm making it many times faster and more efficient than any computer. This is important as adaptive optics control for large telescopes, such as the TMT, is very compute intensive. HIA and the University of Victoria have partnered with Lyrtech to establish that FPGA computers can be used to advantage on TMT-class adaptive optics systems. Building on this work Lyrtech and their astronomy collaborators are now going further to co-develop a large FPGA board and software for broader use in optical and radio astronomy and in many other applications.

These very successful collaborations are contributing to the company's reputation, are opening new markets for Lyrtech, and are enabling the development of new product lines by lowering the cost and risk of a large research and development. Such large steps are very risky for SMEs to undertake alone. The work in astronomy is helping to develop other applications within the scientific community including wireless communication.

## TeraXion – Sherbrooke, Québec

TeraXion Ltd. has been involved in LRP projects since 2003, contributing the laser system in the antennas for ALMA and a high-end system that will be used to test the ALMA antenna front-end receiver system before final deployment. Upon completion of these contracts, TeraXion will have earned revenues of more than \$5 million from this LRP work. TeraXion is now identifying other markets that may benefit from the products and technologies

resulting from this LRP work, including in the defence and aerospace industries.

## COM DEV – Ottawa, Ontario

COM DEV, the largest Canadian-based designer and manufacturer of space hardware subsystems, has been involved in space science since 1985. The company brings capabilities in areas such as digital processors, optical systems, EMC (Electromagnetic Compatibility), reliability and electronics. Contributions to astronomy projects include the Fine Error Sensor Camera for FUSE (a U.S. ultra-violet observatory launched in 1999), a high-resolution spectrometer –HIFI – for Herschel (launched in 2010) and the Fine Guidance Sensor of JWST (successor to Hubble) to be launched around 2015. Canada is a scientific partner in all of these projects.

COM DEV is steadily strengthening its position in this area. In November 2005 it acquired two elements of the EMS Space & Technologies division, including the Ottawa-based Space Science and Optical Instruments business. As a result of this transaction, COM DEV became the prime contractor to the CSA for the Canadian contribution to JWST. In order to reflect the importance of projects like the JWST FGS instrument, COM DEV created a division called COM DEV Canada Space Systems whose mandate is the Canadian space market.

## Ceravalo Optical Systems (COS) – Ottawa, ON

Ceravalo Optical Systems has been a designer and fabricator of custom optics and optical systems for the astronomical and industrial community for 17 years. COS fabricated the optics for MOST, Canada's first space telescope and assisted



in the telescope's assembly and testing. Other space projects COS participated in include the BRITE nanosatellites and NEOSat micro satellite. COS recently entered the realm of metre class optical systems with the delivery of a 1m LIDAR system for Environment Canada.

### **Breconridge – Kanata, Ontario**

Breconridge Ltd. (recently acquired by Sanmina-SCI) is one of the world's top 50 electronics manufacturing companies and a major contractor for the printed circuit boards for the EVLA correlator, a breakthrough in wide band signal processing known as WIDAR. This contribution to the EVLA is a key element of Canada's commitment to NAPRA, and similar correlators are now being provided to other observatories. The EVLA contract alone was worth about \$4 million, and positions Breconridge to obtain a contract for the much larger SKA correlator. These state-of-the-art circuit boards helped to put Breconridge on the cutting edge of technology development in signal processing.

### **Nanowave Technologies – Toronto, Ontario**

As part of the ALMA Band 3 project, Nanowave Technologies successfully produced hundreds of the extraordinarily low noise, very high bandwidth, radio frequency amplifiers (LNAs) and is now marketing this product worldwide for a variety of applications.

The LNA attracted customers outside the astronomy community. For example, the Commissariat à l'Énergie Atomique in France purchased two units for its research into low noise carbon nanotube transistors.

In addition to the LNAs, Nanowave is fabricating the Band 3 mixers for ALMA. The low noise level achieved for these mixers attracted worldwide attention. The 12-m single-dish Arizona Radio Observatory purchased two Band 3 mixers because of their low noise and their unique image rejection. Also, the Combined Array for Research in Millimetre-wave Astronomy (CARMA) purchased Band 3 mixers for one of its polarization channels, increasing the array sensitivity by a factor of two. CARMA is interested in ordering a second set for the other polarization.

### **Murandi Communications – Calgary, Alberta**

Calgary's Murandi Communications optimized the design for the down converter module developed and prototyped for the JCMT correlator by NRC-HIA. This module had extremely demanding requirements compared to those typically required in the wireless communications sector. Murandi made key design modifications resulting in a more compact and less expensive product that could be more readily manufactured. This accomplishment is now used as a marketing tool to demonstrate Murandi's enhanced capability and it has enabled them to enter challenging broadband wireless markets such as Wi-MAX and 4G very early. The WiMAX wireless communication technology market is projected to exceed \$9.4 billion by the year 2015 (ref. 1).

### **Dynamic Structures – Coquitlam, British Columbia**

Designing and building telescopes is an area of expertise first developed by Dynamic Structures Ltd. (DSL) in the 1970s when Canada became a partner in the CFHT and later in the Gemini Twin Eight Metre telescopes. The initial investment in CFHT led to a \$44 million contract for DSL to build the domes for the Gemini telescopes. The structural design expertise generated at DSL on these projects has now grossed over \$300 million from the design, manufacture and construction of twelve of the world's largest telescope enclosures, helping to showcase Canada's scientific and industrial strengths internationally. DSL is currently poised to build the telescope and enclosure for the TMT, creating 850 person years of work.

In one of the best examples of unforeseen economic spin-offs, DSL has since parlayed their experience and expertise working on astronomy projects into becoming a world leader in the design and manufacture of amusement park rides. The company has built rides for Disney, Six Flags and Universal. DSL has generated an additional \$300 million worth of amusement park ride work to date, with another \$300 million in orders pending. Overall, the theme park industry is now valued at \$10 billion in North America alone (ref. 2).

### **Profile Composites – Sidney, British Columbia**

Profile Composites Inc. is working with NRC-HIA to develop a new type of reflector antenna. This antenna's reflector

(1) Deepa Seetheraman, "Schwarzmatt Sees Big Returns in Roller Coasters" published in Reuters, U.S. edition October 18, 2009.

(2) Global Industry Analysts Inc., "WiMAX: A Global Strategic Business Report", Report MCP-6118, April, 2010.

uses composite materials instead of metal, making it an innovative and competitive candidate for the roughly 3000 antennas needed for the SKA. This effort is related to one of the work packages assigned by the international SKA design team to produce a demonstration antenna. The design/build of the SKA composite antenna system represents a potential \$150-300 million opportunity.

The SKA requires antennas in a new cost-performance regime. They must be large, high-performance and low-cost. Achieving this requires they be high strength, low weight, and have low thermal expansion properties. They also need to be efficiently manufactured because of the large number of units required. These requirements drive the need for use of composite materials for these antennas.

Profile Composites is already a major contributor to advanced composites technology for applications in wind turbine blades, and in automotive and

aerospace applications. It is a member of major international research consortia that include other companies such as Bell Helicopters, Boeing and Bristol Aerospace. It thus potentially brings to the table major international suppliers of materials and expertise to the design of composite materials antennas for large scale radio astronomy and wireless communications systems, resulting in a synergistic partnership between industry and the radio astronomy community.

### **Daniels Electronics – Victoria, BC**

Daniels Electronics Ltd. specializes in the design and manufacture of customized low power radio communications systems operating in rugged environments and extreme temperature conditions. In 2008 Daniels Electronics was awarded a \$1.3 Million contract for the assembly and test of Band 3 84-116 GHz heterodyne receivers for the ALMA telescopes.

## **Appendix G – ESO Working Group Report**

The ESO Working Group visited ESO in July 2010 for the purpose of assessing the possibility and implications of Canada participating in the E-ELT project. The Working Group issued a report in August 2010 that can be found at:

**[http://casca.ca/lrp2010/Docs/ESO\\_WG\\_report.pdf](http://casca.ca/lrp2010/Docs/ESO_WG_report.pdf)**

Appendix 5 of the report is in a separate document:

**[http://casca.ca/lrp2010/Docs/ESOWG\\_Appendix5\\_TMT\\_EELT.pdf](http://casca.ca/lrp2010/Docs/ESOWG_Appendix5_TMT_EELT.pdf)**





