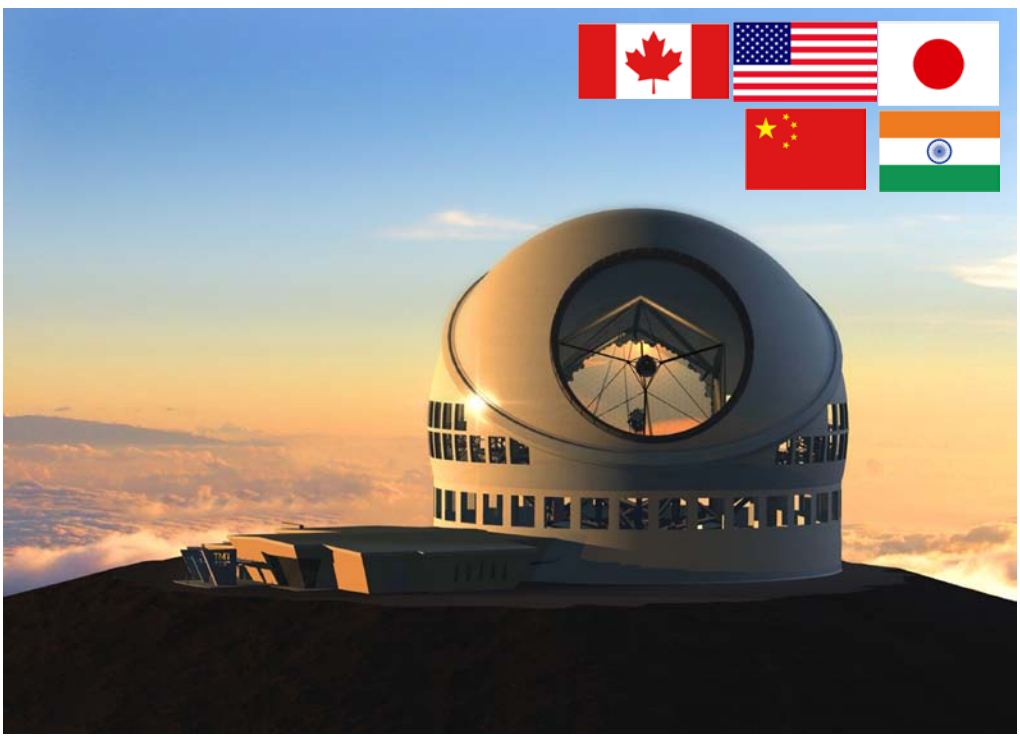
THE THIRTY METER TELESCOPE AND ASTRONOMY IN CANADA

A REPORT TO THE NATIONAL RESEARCH COUNCIL

BY

THE ASSOCIATION OF CANADIAN UNIVERSITIES FOR RESEARCH IN ASTRONOMY



Rendering of The Thirty Meter Telescope showing the iconic enclosure design by Dynamic Structures Ltd. of Coquitlam, B.C. The enclosure will be a Canadian contribution to the project.

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Annexes to the Report

Acronyms and Abbreviations used in the Report

AAT	Anglo-Australian Observatory
ACURA	Association of Canadian Universities of Research in Astronomy
ARC	Average Relative Citations
ARO	Algonquin Radio Observatory
ALMA	Atacama Large Millimeter Array
Caltech	California Institute of Technology
CASCA	Canadian Astronomical Society
CCA	Council of Canadian Academies
CGEP	College d'Enseignment Général et Professionnel
CFHT	Canada France Hawai'i Telescope
CFI	Canada Foundation for Innovation
CFRS	Canada France Redshift Survey
CITA	Canadian Institute for Theoretical Astrophysics
CSA	Canadian Space Agency
CTIO	Cerro Tololo Inter-American Observatory
DAO	Dominion Astrophysical Observatory
DDO	David Dunlap Observatory
DDP	Detailed Design Phase
DRAO	Dominion Radio Astrophysical Observatory
E-ELT	European Extremely Large Telescope
ESO	European Southern Observatory
GMT	Giant Magellan Telescope
GPS	Global Positioning System
HAL	Hickling Arthurs Low
HIA	Herzberg Institute of Astrophysics
HPC	High Performance Computing
IAU	International Astronomical Union
ICT	Information and Communications Technology
JCMT	James Clerk Maxwell Telescope
JWST	James Webb Space Telescope
KPNO	Kitt Peak National Observatory
LRP	Long Range Plan
LSST	Large Synoptic Survey Telescope
MMT	Multiple Mirror Telescope
NFIRAOS	Narrow Field Infrared Adaptive Optics System
NRC	National Research Council
NSERC	Natural Sciences and Engineering Research Council
NSF	National Science Foundation

Acronyms and Abbreviations used in the Report (cont'd)

Pan-Starrs	Panoramic Survey Telescope and Rapid Response System
RTO	Research Technology Organization
S&T	Science & Technology
SFU	Simon Fraser University
SMU	Saint Mary's University
SKA	Square Kilometre Array
SNLS	Supernova Legacy Survey
SRO	Special Research Opportunity
SRP	Strategic Research Plan
TMT	Thirty Meter Telescope
UBC	University of British Columbia
UC	University of California
UNB	University of New Brunswick
UQAM	Université de Québec à Montréal
UVic	University of Victoria
VLBI	Very Long Baseline Interferometry

PREFACE

This report emerged from discussions between the Association of Canadian Universities for Research in Astronomy (ACURA) and the National Research Council (NRC). The purpose is to provide the perspective of ACURA's member universities on the Thirty Meter Telescope (TMT) and its impact on Canadian astronomy. The report was prepared for NRC to assist with their preparation of the business case for TMT for submission to the Federal Government.

The report was prepared by an ACURA Working Group consisting of six members, four of whom were members of the LRP 2010 Panel and two others with expertise on the TMT project. The members, in alphabetical order are:

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Contributions by Neil Rowlands, Com Dev International are gratefully acknowledged.

June 30, 2013

1. International Aspects and Canadian Leadership

1.1 Canada's Standing and World Leadership in Astronomy and Astrophysics

That Canada shines by its performance in astronomy and astrophysics has recently been ascertained in extensive studies by the Council of Canadian Academies (CCA) and, under contract to the NRC, by the firm Hickling, Arthurs & Low (HAL). Extracts from these studies are found in Annex 1-A and Annex 1-B (see end of report).

Both studies confirm that Canadian astronomers and astrophysicists rank first in the world by the impact of their scientific discoveries. The HAL Report recognizes that access to world class facilities enabled by the support of the NRC, the CSA and of the granting Councils, NSERC and CFI, has been pivotal to the maintenance of the international reputation Canada enjoys in astronomy. However, the Report also points out that "The costs of next generation facilities are greater [than that of former facilities] and at the outer reaches of affordability even with international partnerships." There is then cause for concern in trying to keep Canada competitive in a discipline where it currently excels and where furious competition exists in advanced and emerging countries. As the HAL Report notes: "In recent years, as a percent of gross domestic product, five countries – the United Kingdom, Italy, France, Germany and the United States, – spent at least twice that of Canada in capital for astronomical facilities. In operations support, these same countries spent four times that of Canada."

The milestones in achieving this leadership include the "game changing" facilities and institutions that have historically contributed to Canada's capacity to engage in astronomy (DAO, DDO, CFHT, CITA, and Gemini). The history and role of such facilities is described in: http://www.cascaeducation.ca/files/historyAstronomyCanada.html.

The history of the Canadian – or of any national – astronomy program vividly illustrates how progress hinges on access to world-class facilities. At the start of the twentieth century, Prof. C. A. Chant of the University of Toronto realized that the future of astronomy lay in astrophysics and established a separate astronomy department at the University of Toronto. At the same time W. F. King, Canada's first "Chief Astronomer", also recognized that research was expanding beyond the traditional fields of time and position. He persuaded the Federal Government to establish the Dominion Observatory in Ottawa and to equip it with a 38 cm refractor. This was Canada's first centre for astrophysical research with solar and stellar spectroscopy being the main areas of study.

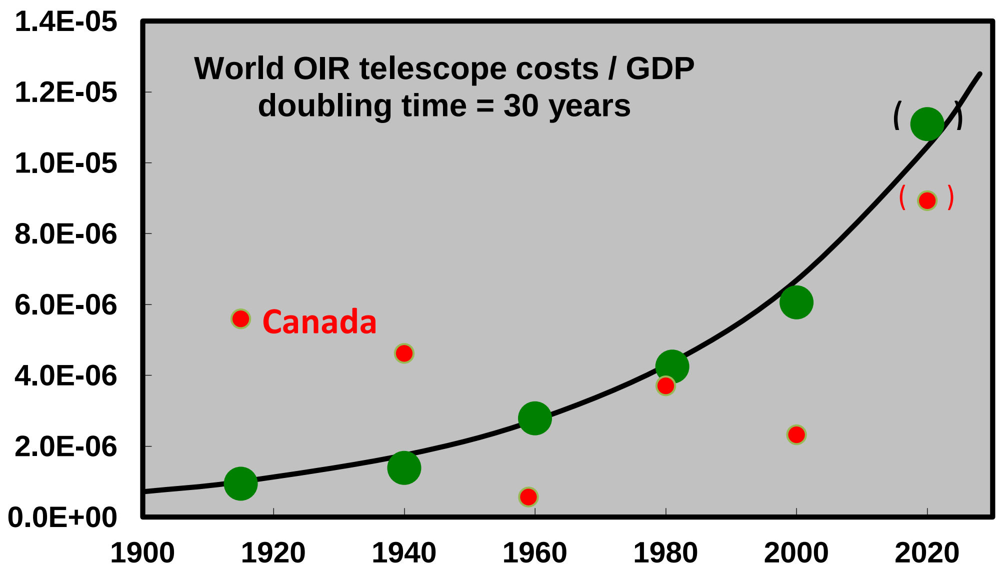
The limitations of this rather small telescope in a poor environment soon frustrated one of the astronomers, J. S. Plaskett who knew that a large reflector telescope was needed, and through his efforts, the "second to none" Dominion Astrophysical Observatory (DAO) was opened near Victoria, B.C. in 1918. Its 1.8 m telescope was one of the largest anywhere for several decades. Plaskett's work on the rotation of our Galaxy brought world-wide recognition to him and his observatory. The powerful DAO telescope allowed astronomer Andrew McKellar to measure the temperature of "deep space" in1940: his estimate was 2.4°K. Had the physics been ready by then, this would have been recognized as the residual temperature of the Big Bang, 28 years before its re-discovery by Princeton Nobel laureates Arno Penzias and Robert Wilson.

Meanwhile, Prof. Chant achieved a lifelong dream in seeing a major observatory established at the University of Toronto. The David Dunlap Observatory (DDO) opened in 1935. It housed the second-largest telescope in the world. For many years, it was the only facility in the country where a student could get training in astronomy.

In the 1970s all government astronomy became the responsibility of the National Research Council (NRC) in the newly organized Herzberg Institute of Astrophysics (HIA), named for Nobel laureate Gerhard Herzberg. Professional astronomers now numbered over one hundred, and the community decided to form their own organization – the Canadian Astronomical Society (CASCA).

As increasingly larger and more expensive (Fig. 1-1), facilities became necessary for frontier research, the only way that institutions could afford to keep up was to cooperate in shared ventures. The Canada-France-Hawai'i Telescope (CFHT) was the first such venture in 1979, followed in 1983 by the James Clerk Maxwell Telescope (JCMT), both in Hawai'i, and by the Gemini Observatories in Hawai'i (2001) and Chile (2003).

Figure 1-1: The cost of world-class telescopes, in real GDP dollars, doubles in 30 years.



The growth of "Telescope Power" per capita for Canada, the USA and Europe since 1900 is illustrated in the Figure 1-2 below. For comparison, we also show in Figure 1-3[1] the normalized number of astronomers in IAU member countries. The data are from compilations by ACURA Secretary-Treasurer René Racine from many sources, including privileged information. They clearly show how the quest for discoveries has historically driven astronomers to develop increasingly larger, more powerful and more costly instruments. Canada's "Telescope Power" per capita has slipped below that of the USA after the advent of the Palomar 200-inch telescope in 1949 and below that of European nations with the commissioning of their Very Large Telescope (VLT, 4 x 8-m) in the late 1990s. But continued access to world class facilities, communal selectivity in research orientations and plain hard work have allowed Canada to remain first in the world by the impact of its astronomers' discoveries.

[1] The relative populations of astronomers (members of the International Astronomical Union per million of population) are similar for Canada (6.8), the USA (7.9) and the G20 European nations (6.7). For all of Europe it is 5.1.

The enlightened and at times heroic support of federal agencies (NRC, CSA, CFI and NSERC) in enabling access to facilities has helped to assure the future performance of Canadian astronomy. The community's 2000 Long Range Plan (LRP) for Canadian Astronomy recommended participation in the Atacama Large Millimetre Array (ALMA), which the NRC pursued. ALMA is now operational.

The 2005 and 2010 LRP reports recommended a 25% partnership in an Extremely Large Optical Telescope, now identified as TMT. Support from NRC, NSERC and CFI made it possible for Canada to fully participate in the Design and Development Phase (DDP) of the TMT. As the partnership has expanded, Canada's proposed share has necessarily dwindled slightly. Figures 1-1 and 1-2 assume federal funding for a 20% share of TMT.

Joining the international collaboration in the Square Kilometre Array (SKA) of radio-telescopes was another leading LRP priority – this one in radio astronomy. Through NRC, Canada is now a member of the SKA development team.

Finally, the support of the CSA has enabled Canada to join the James Webb Space Telescope (JWST) collaboration, thereby ensuring access to the leading space observatory of the 2020s and beyond.

Figure 1-2: "Telescope Power" per citizen since 1900 for Canada, the USA and Europe.

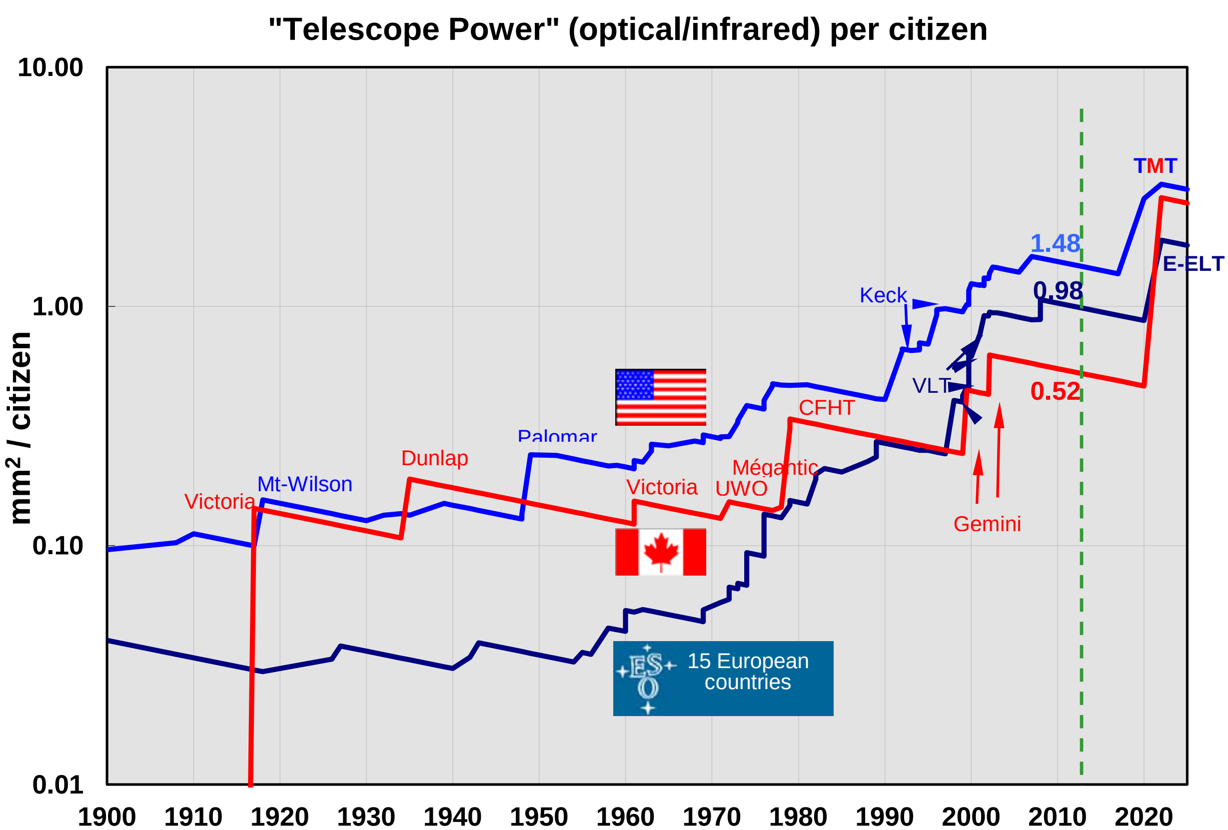
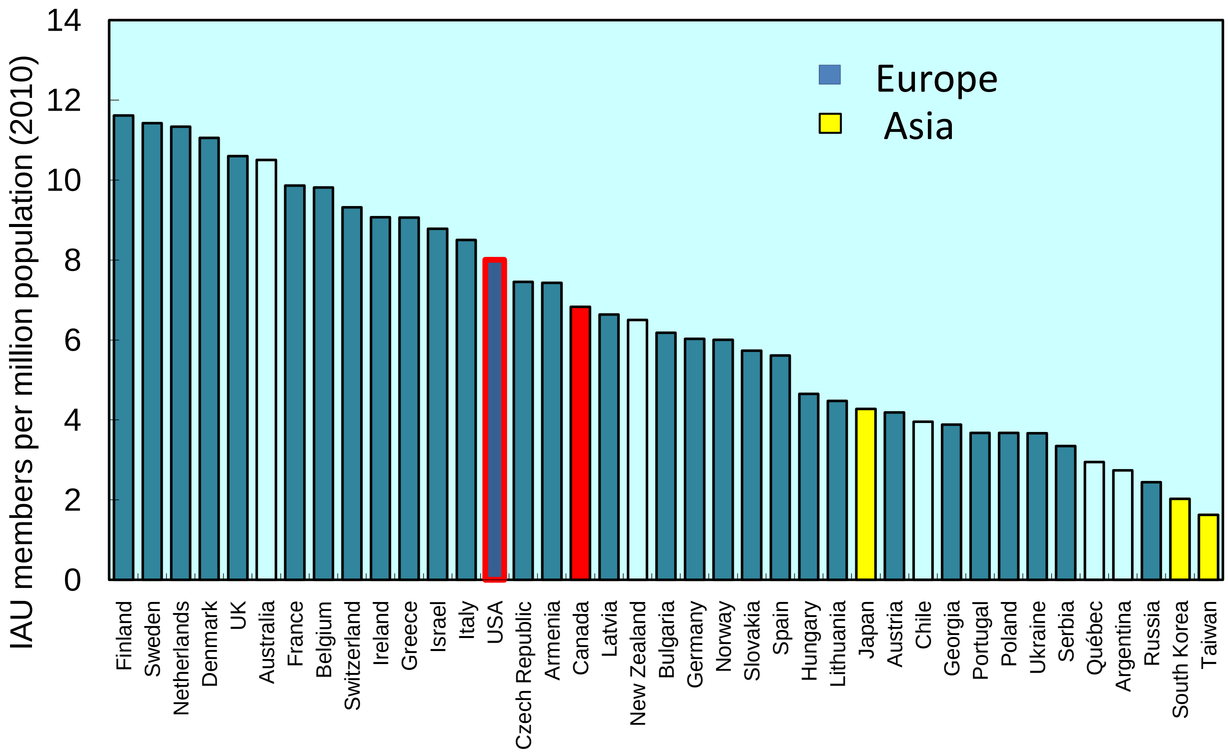


Figure 1-3: Relative population of astronomers in various countries.



The groundwork for today's leadership was laid also by the vision and work of many astronomers over decades through to the present. There are many exciting stories underlying transformative developments in Canadian astronomy. The following examples are representative but far from complete:

In 1967 Canadians made a major contribution to radio astronomy by performing the first successful experiment in **Very Long Baseline Interferometry (VLBI)**, involving antenna spacings of continental dimensions to achieve very high angular resolution. The technique requires independent recordings of the antenna signals and later correlating the recorded signals at a processing site. The primary obstacle to achieving this was the lack of adequate recording bandwidth in commonly available signal recorders. However, J.L. (Allen) Yen, and H.P. Gush at the University of Toronto, and collaborators at Queen's University and Federal Government observatories, acquired three de-commissioned video recorders donated by the CBC, as they converted to colour broadcasting. These permitted a successful recording of fringes on the quasar 3C 273 using antennas at the Algonquin Radio Observatory (ARO) and the Dominion Radio Astrophysical Observatory (DRAO). The team received the 1971 Rumford Medal for this accomplishment.

In the 1980's cosmologist Richard Bond came to Canada to join the new Canadian Institute for Theoretical Astrophysics ((CITA) with a vision for studying the (as yet undetected) **fluctuations in the Cosmic Microwave Background** (CMB) as a precise way to measure cosmological parameters. His foresight led to a change in the design of the COBE satellite to make it more sensitive to fluctuations which were expected to be very weak. The COBE satellite measured the fluctuations and the COBE experimenters were recognized with Nobel prizes. As follow-up Bond led the way to a series of experiments that has now been fully realized with the Planck satellite and a complete set of high precision measurement of six key parameters that describe the expansion and contents of the universe. Through Bond's influence Canada has a very strong community of CMB experimentalists that have reaped Gruber prizes not just for himself, but for his Canadian co-workers.

In the past decade a direct contributor Canadian leadership is the project known as the **Supernova Legacy Survey (SNLS)** which led to a characterization of the accelerated expansion of the universe. New developments at the CFHT provided a wonderful confluence of opportunities. The acceleration of the universe had just been discovered in 1998. In 2000 the term "Dark Energy" was coined to account for the effect. At the time CFHT was developing a very large imager (MegaCam) and looking for ways to maximize impact in return for the considerable financial investment. A group of astronomers in Canada and France realized that they had an opportunity to take a very large step forward, essentially equal to some ideas for satellite missions of the time, to make the first good measurement of how Dark Energy varied with lookback time in the universe. The SNLS led to the most highly cited paper ever based on work done with predominantly CFHT data. It also was in the Astronomy and Astrophysics "Volume 500, celebrating 40 high impact papers over 40 years (see the following, http://www.aanda.org/articles/aa/full_html/2009/22/aa12466-09/aa12466-09.html)

As noted earlier, these examples tell only part of the story. There are many other major contributions to Canadian astronomy, not fully developed in the stories here, but we mention them because of their impact on Canadian leadership. Examples include the pioneering developments by René Racine on adaptive optics on the CFHT, the Canada France Redshift Survey by Simon Lilly leading to a characterization of the evolution of the universal galaxy luminosity function, and the pioneering work this decade on the imaging of exoplanets by René Doyon and Christian Marois.

ACURA universities are also playing an important role in maintaining the continuing Canadian leadership in astronomy. The excellence of university astronomers makes Canada a desirable partner in international projects. The initiatives for participation in TMT and in SKA arose in universities and have been strongly supported by the ACURA Board and Institutional Council. ACURA managed the Canadian contributions to the TMT DDP, with support from the Herzberg Institute of Astrophysics, and appointed the Canadian members of the TMT Collaborative Board and committees. The Canadian SKA Consortium and its Board were created by ACURA universities as was the recent industrial consortium engaged in TMT-Canada.

The Canadian astronomical community has demonstrated that it musters the organization and the talents to maintain the leadership of the country in world astronomy as long as ACURA universities and NRC Herzberg (formerly HIA) are provided with the required support by governmental agencies. Canadian astronomy has attracted the best and has provided the best training over many decades, motivating young generations for careers in science, technology, engineering and mathematics and teaming with industries in the development of frontier technologies. The choice of maintaining this leadership is that of politicians who must weigh the relative merits of numerous projects competing for taxpayers' money. This document aims at informing that choice.

1.2 Interdependence of Leadership and Quality of University Programs

One of the most common themes and goals of the Strategic Research Plans (SRPs) of ACURA universities is leadership. Without leadership there is no world recognition, and the plans of our nation of universities cannot be sustained. Accordingly, a primary goal of ACURA is to maintain the leadership in astronomy and astrophysics of its member universities. Leadership feeds on itself. Once an institution has managed to become recognized as hosting world leaders in a discipline, it can establish collaborations with peer groups abroad, attract well established or highly promising faculty members and support personnel and strengthen relations with industries at home and abroad. This ensures the continued excellence of university research and training programs. ACURA universities host internationally recognized groups in many astronomy sub-disciplines where such synergism is at work. Areas where ACURA universities now exert a leadership role include: (1) ground and space astronomical instrumentation, (2) galaxy evolution, (3) cosmology, (4) exoplanets, (5) stellar structure, and (6) computational astrophysics.

1.3 Retention of Leadership – What are the Risks?

Canada's current leadership in astronomy and astrophysics is not guaranteed to be sustained without adequate resources to enable our researchers to flourish. The risks to loss of leadership include:

- *Loss of access to competitive international facilities*: Access to international facilities is a bootstrap process: it is granted in competitions where success critically depends on having had such access. Canadian astronomers have succeeded in this competition because the country has invested in its own world-class facilities in the first half of the 20th century (DAO, DDO, DRAO, ARO), thereby opening the door to joining larger international projects later (CFHT, JCMT, Gemini, ALMA, JWST). Participation in TMT, and in SKA, must be seen as the continuation of the process, securing in the future the leadership Canadian universities have established over the last century.

- *Inadequate support from national agencies*: Canadian universities have acquired and maintained leadership in astronomy largely thanks to the support of national agencies. But this is also a bootstrap process: the allocation of funds is competitive and depends on the production of important discoveries, of results that fascinate taxpayers and of performances that impress decision makers faced with difficult "arbitrages". It is, of course, less difficult to retain leadership when the tools necessary to perform leading activities are accessible. In this respect, the suspension of the NSERC SRO program – which has been crucial to ACURA's evaluation of the TMT option – is making it extremely difficult for university groups to explore new initiatives. In addition there is concern in the scientific community that the restructuring of NRC into an RTO and the move away from basic research will lead to sacrifices in NRC's ability to carry out its statutory mission in supporting our national and international observatories. ACURA urges that NRC maintain a strong stewardship in supporting this activity which is vital to the universities in contributing to Canada's leadership in astronomy.

1.4 The Role of Continuous Planning in Maintaining Leadership

It is sometimes asked whether it is reasonable for the astronomy community to propose a partnership in a large international project like the TMT on the heels of an earlier project like ALMA which is not yet finished and barely producing science. The answer to this and similar questions goes to the heart of the planning process. All nations with a strong track record in science produce decadal plans or their equivalent which serve to map the future development of the field over 10-20 years. The aim is to make wise investments, and to ensure available shares in a full array of scientifically complementary facilities. Such plans are openly available and thus ensure that each nation knows the plans of the others. No one nation can afford the largest telescope facilities now needed to advance astronomy and so international cooperation is desirable and essential.

Examples include Canada's own LRP:
(http://casca.ca/wp-content/uploads/2012/12/11093_AstronomyLRP_V16web.pdf),
the US Decadal Survey:
(http://www.nap.edu/catalog.php?record_id=12951),
and the European Astronet Roadmap Plan:
(http://www.astronet-eu.org/FP6/astronet/www.astronet-eu.org/IMG/pdf/Astronet-Book.pdf).

While all such surveys necessarily rank all projects according to merit, not all surveys provide the same rankings. For example, while the LRP ranked a very large optical/IR telescope (VLOT) and SKA highly, as did Astronet, the US survey placed a VLOT second among large ground based facilities, and the SKA was not even ranked. The US, in ranking the smaller aperture Large Synoptic Survey Telescope (LSST) as number one, recognized the equivalent importance of wide field and high data capacity in advancing several research areas, and the complementarities to the larger narrow field telescopes such as TMT. Thus such differences provide new opportunities for cooperation in meeting broader scientific goals. Even when there appears to be direct competition, such as in the case of the TMT and the European Extremely Large Telescope (E-ELT), there are enough astronomers in the international community to oversubscribe both telescopes, and new opportunities for global cooperation by outfitting these telescopes with complementary instruments.

This brings us to the question posed at the beginning of this section concerning overlap in timing, planning and execution of "world observatories". The various international plans are aimed at providing a powerful international complement of facilities to answer the biggest scientific questions in the most complete way possible. The timing of projects is driven by the science and by opportunities for scientific partnerships. Development and construction of some projects will inevitably overlap with others. In some cases such as the SKA, the facility will not reach its full potential for decades, even if construction begins soon, while the TMT must be built and utilized now on a shorter time frame to realize the full benefit. This process is now the norm for engagement in planning world observatories and the world leaders must engage in it to retain their leadership.

1.5 The TMT as Canada's Immediate Priority for Participation in a Ground Based Facility

The TMT is a natural fit to Canada's needs as a major player in astronomy. It follows on the heels of a Canadian partnership in the world's premier mm/sub-mm observatory - ALMA, and precedes a partnership in a unique radio array – the SKA. While complementary in wavelength to these radio facilities, the TMT has its own unique science case (http://www.tmt.org/). The case is made significantly more powerful by a unique adaptive optics system, NFIRAOS, yielding near diffraction limited images in the near IR. NFIRAOS will be a Canadian (NRC) contribution to TMT. When used for observing faint unresolved sources, NFIRAOS will increase the scientific productivity of the telescope from a D^2 to a nearly D^4 dependence, thus taking exceptional advantage of the large aperture diameter D of the TMT.

As an optical-IR facility the TMT is a natural fit to the major strengths in Canada's largest astronomy groups among the ACURA universities, for e.g. University of Victoria, University of British Columbia, University of Toronto, Université de Montréal and Laval University. These are also the major centres of university optical-IR instrument development. UBC and Toronto, together with NRC, also conducted a $25M design study leading to the Canadian contributions identified in the project business plan, and to ACURA's strong role in the project. Canada's total investment to the preconstruction phase (prior to 2014) will amount to more than $30M.

There are important synergies between TMT and other world projects such as ALMA, SKA, Herschel, and the forthcoming space telescope JWST, all of which involve Canada. These synergies provide the benefits of investigating the same phenomena at different wavelengths at comparable resolution, essential for a more complete understanding, as noted in section 1.4. These other world projects may even lose much of their impact without access to TMT. An example is clearly expressed in the TMT NSF Proposal[2], which describes how observations combined from different telescopes are necessary to understand how the first stars formed in the universe. By combining TMT, SKA and JWST observations it will be possible to trace the different stages in this process which are visible in the different wavebands detected by these telescopes. The full text reads as follows:

"The Square Kilometer Array (SKA) will survey the three-dimensional distribution of neutral hydrogen during the "Dark Ages" over wide swaths of the sky with a field of view of 1 deg^2 and a spatial resolution less 0.1 arcsec. TMT will observe the First Luminous Objects to emerge from these Dark Ages on similar resolution scales. SKA will also survey sources at the microjansky and nanojansky levels (Padovani 2011) [9], and these sources are expected to be so optically faint that TMT will be required for spectroscopic follow-ups. It will then be possible with TMT+SKA to study star formation rates and feedback from active galactic nuclei in normal galaxies out to z = 6. JWST and TMT will be another powerful combination for the study of First Light. The field of view (3-arcmin) and the sensitivity of JWST out to mid-infrared wavelengths will be ideal for detecting those very distant objects that are also expected to be very small (sizes ≤ 80 to 100 milliarcseconds with redshifts z > 10-20). Multi-slit spectroscopy on TMT is key for

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[2] *Planning a US Partnership in a Thirty Meter Telescope Project.* This proposal was submitted to NSF in April, 2012 to respond to a solicitation by NSF. It is not a public document, but available from TMT Corp. on request.

determining mass/kinematics, metallicity, outflows, and the initial mass function of these distant objects. The diffraction-limited image size provided by TMT is a good match to the size of a HII region at these redshifts. Even an extremely large telescope will not reach down to the level of the continuum, and TMT observations will be complemented by spectral energy distributions from JWST broad-band imaging to secure equivalent line widths. Deployable, AO-assisted IFUs on TMT will also be able to map large ionized bubbles around JWST sources to characterize the topology of re-ionization. With its capability to image dust continuum to a redshift of z = 10, ALMA will provide complementary information about the content of JWST/TMT sources for a full baryonic inventory."

There are also synergies with, and potential for cooperation with, the European Extremely Large Telescope (E-ELT), the Giant Magellan Telescope (GMT), and the Large Synoptic Survey Telescope (LSST), and future high energy astrophysics missions. An example of synergy with the LSST, again discussed in the NSF TMT proposal, reads as follows:

"Time-domain astronomy (e.g., Pan-STARRS, LSST, gamma and X-ray space missions) holds significant discovery potential, and very wide-field synoptic surveys are expected to produce very large numbers of transient detections that require rapid follow-up. Most of the discovery space for cosmic transients (the "Unknown Unknowns") actually lie in the domain of very fast (2 minutes ≤ decay time ≤ 2 hours) transients [Figure 8.6, LSST Science Book]. One of the LSST mini-surveys will cover a small number of 10 deg^2 fields every ~15 seconds for about an hour out of every night to catch some of these very fast transients. TMT is being designed as a rapid response system to a vast array of transient events with stringent requirements for short slew and acquisition times and short active/adaptive optics systems configuration times."

There is also potential for synergy between TMT (and other world observatories) and theoretical and computational astrophysics in Canada, notably involving observations and theory of star and planet formation and galaxy evolution. For example, to quote from the LRP2010:

"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.",

and:

"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.".

1.6 The International Climate for the TMT

The TMT partnership has developed into an exciting new Asia-Pacific relationship between scientific institutions in the USA (Caltech, the University of California, and Yale University, with the US

National Science Foundation considering joining), Canada, Japan, China and India. The current ownership share scenario (percent) is shown in the table below, but this is likely to change somewhat as each partner makes its own funding decisions and possibly new partners emerge. The project will defer some elements to reduce the initial cost and enable the project to begin without guaranteed participation of the NSF, although there remains an opportunity for them to join.

Canada	19.6
China	8.6
India	10.1
Japan	19.1
UC/CIT	25.5
Yale	4.4
New Partner(s)	12.6

In January 2013, the Indian Secretary of the Department of Science and Technology addressed the TMT Collaborative Board to explain that his country was joining to provide a beacon to attract young people to careers in science and technology, to help provide them with better lives and to help to continue to propel the whole country forward to a future working and competing with the very best that the world has to offer.

1.7 The Importance to Canada of a 20% Partnership in the TMT

Large ground-based telescopes are central to frontier astrophysics. They challenge technology and instrumentation development and continue to be a beacon inspiring everyone from school age onward. Much of Canada's strong reputation in astronomy is based on the tremendous success of the uniquely powerful Canada-France-Hawai'i Telescope (CFHT), opened in 1979. CFHT has now been largely overtaken by newer and larger telescopes, although CFHT continues to play an important role. In the late 1970s and onwards many universities in Canada recognized the powerful advantage that CFHT provided, and developed astronomy programs based on this common resource. As a result Canadians helped move the scientific frontier in imaging science forward beyond the capabilities of other telescopes. Moreover, the benefits to both researchers and students of international collaboration are now well understood in Canada.

The Chief Astronomer of Canada in 1912 called for a telescope "second to none", which has been an important concept to allow Canadian astronomers to focus resources on a few facilities where we can play a major role, and which then can leverage access to the entire array of international astronomical facilities. Canadians joined the TMT project in 2003 as equal partners and we have maintained our share of the project at about the 20% level over the last decade. Having a significant share is absolutely crucial in helping us promote our scientific vision for the current use and future development of TMT. These arguments are fully developed in the Canadian Long Range Plan for Astronomy of 2010.

How can one quantify the benefits of the telescope time shares in order to justify a specific share such as 20% of the TMT? For example, how would we compare a 20% share in TMT with a 10%

share in the SKA or a 2.5% share in ALMA? It is important to understand that the latter are unique world facilities, whereas the TMT class telescopes will not be unique. There will ultimately be a collection of such telescopes of comparable collecting aperture. Thus comparisons should be made on the basis of equivalent fractional share of the total collecting aperture among TMT class telescopes. A similar basis should be used for comparing the instrumental power in this new era with those in earlier eras of 8-m and 4-m telescopes, which were so essential in establishing Canada's current leadership in astrophysics.

With this idea in mind, particularly for item (1) below, we can quantitatively list the benefits of a 20% share in the TMT from a number of perspectives:

1. A 20% share of TMT corresponds to a 5.9% equivalent share of the entire Extremely Large Telescope primary mirror area, once TMT, the European ELT and the GMT are built. This share is slightly smaller than the 6.5% of clear sky fraction-weighted mirror area we had in the 4m era (1950-1990) when there were seven comparable aperture telescopes (Hale, KPNO, CTIO, AAT, ESO 3.6m, MMT and CFHT). If the site qualities ("seeing") are taken into account, the superior CFHT site provided Canada 11% of the "telescope power" (science per unit time[3]) in the 4-m era. Note that in the TMT class era, all such telescopes will be located at excellent observing sites and will benefit from similar clear sky fractions (~80%) and excellent seeing. In the current 8-m era (1990-2020), there are 16 comparable telescopes and Canada's 20% share of Gemini provides us with an equivalent share of 2.8% of the total collecting aperture, and thus 2.8% of the total science per unit time. Thus, in terms of world shares, a 20% share in TMT (5.9% of world capability) brings us to half the share of world capability we enjoyed in the 4-m era (11%) and twice the one we have today in the 8-m era (2.8%).

   Looked at from the viewpoint of scientific productivity, one can make a direct comparison between the productivity of a 20% share in TMT with that of one of our existing telescopes to illustrate the enormous gain in competitive telescopic power of a significant share in TMT. For example, a 20% share of the TMT will provide Canada with 33 times more science per unit time than the CFHT, taking account of our 42.5% share, assuming the two telescopes are used the same way. In addition, with much more sensitivity, the TMT pushed to its limits observing at the faintest levels, we will be addressing scientific questions that cannot be addressed with any currently existing telescopes. It is clear that existing 4-m and 8-m telescopes in the new TMT class era will be useful at the scientific forefront only if they can be modified to new uses such as wide field capability.

2. One of the benefits of 20% share is that it ensures that we play a commensurate role in both the governance and scientific direction of the observatory. It is comparable to the shares of Caltech and UC (who are jointly funded through the Moore Foundation), Japan, and possibly the NSF at some future phase of the project. This in turn ensures that:
   a. We have adequate observing time to ensure the scientific productivity of the expanding Canadian community which has much of its strength in the areas that TMT will support.

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[3] "Science per unit time" is defined as the reciprocal exposure time on a given object required to reach a particular signal to noise ratio.

This is critical to the researchers and their students. A 20% share would still amount to only about 1/4 night per year per Canadian astronomer (as measured by IAU membership).

b. It allows us to leverage TMT observations into collaborations which make use of other ground based and space missions.
c. We are able to play significant roles in the development of new instrumentation. This has already been demonstrated by our influence on the designs of the telescope, enclosure and adaptive optics system. Frontier facility instrumentation is central to the ongoing engagement with industry and to develop both our scientific and engineering capabilities. For instance, our 42.5% of CFHT allowed us to help improve the telescope for our needs to the point where it became a scientifically dominant facility, effectively competing even in an era of 8m telescopes.

3. A 20% share is viewed internationally to indicate that we are “pulling our weight” in the overall development and funding of scientific facilities. Since Canadian funding of major facilities is highly selective, our access to facilities funded by other nations is dependent on taking this approach.

4. A 20% share of TMT is a natural fit to the capabilities of Canadian industry and advanced optical technology , and is essential if we are going to fully engage and exploit Canadian industry and high technology companies. In addition, Canada undertook a costly design study which produced the design of the enclosure and the world leading NFIRAOS adaptive optics system.

1.8 The Urgency of a TMT Construction Start in 2014

The TMT project has been technically ready for construction for the past few years. In the summer of 2012 the USA’s NSF officially selected the project as its preferred partner for a Giant Segmented Mirror Telescope and has now finalized the award and started funding to develop the US role in the partnership. The site permit for construction was approved in April 2013. For the past year all partners have been in discussions with their funding agencies and political decision-making levels to develop support for the 2014 construction start. The construction plan is approximately 90% funded, with the NSF and potentially others interested in joining. At this time the financial variance is at about the level which the TMT Board can and will need to manage over the construction phase. Delay will mainly increase costs and will not provide any new guarantees.

The proposed Canadian in-kind work includes the iconic TMT telescope enclosure, which is the first item to be erected on the site and is on the critical path almost from the outset of construction. It is critical that Canadian funding be guaranteed at the outset of the project to ensure that the enclosure work is secured for the benefit of Canadian industry, for our share of the project, and for cooperative leadership of the project.

2. Highly Qualified Personnel

This section is somewhat different in nature and purpose from the other sections. It documents demographic trends in astronomy and other disciplines in Canada and other closely related countries. The purpose of the first part of this section is not to promote or support the case for the TMT per se, but to document the demographic evolution that forms a backdrop to astronomy in general, and may be drawn upon to support any number arguments for developments in the field. The section shows that overall the growth across fields and across the world are very similar, though the absolute numbers are of course very different. We do not explore the reasons for the demographic trends, but a likely contributing factor in astronomy for example, is the increasing research diversity reflecting the increasing breadth of wavelength coverage and development of computational astrophysics.

The second part of the section deals with astronomy as a launching point for careers in other fields, and with testimonials of successful entrepreneurs who began their careers in astronomy. This subject is highly relevant to an assessment of the value of astronomy in training students in the use of skills and tools applicable to a broad range of science and engineering. The testimonials are quite remarkable in their common assessment of the key elements for success – curiosity, the drive to understand, engagement with skills and tools to solve problems and make progress.

Canada's success in astronomy is strongly associated with the strength of its human resources and the training schemes that have been developed. Research directions are primarily determined by PhD educated scientists, working in universities or research institutes (such as the Herzberg Institute for Astrophysics). While the largest sector in this group is tenured faculty, it is important to emphasize that post-doctoral researchers play a central role in research productivity. Similarly, research-based graduate students also contribute extensively to the success of the astronomy community.

In terms of the engagement of the wider public in astronomy research, the value of "citizen science" is burgeoning. But more importantly, astronomy is perhaps unique in that it already has an extensive amateur community (the Royal Astronomical Society of Canada and Federation de Astronomes Amateurs du Quebec, together boasting almost 6000 members). Many of these individuals are highly technically skilled and contribute to research projects such as comet and supernova discovery. Indeed, the youngest ever discoverer of a supernova is Kathryn Gray of New Brunswick, who was 10 years old when she discovered supernova SN 2010lt.

In the following discussion we nonetheless focus primarily on the professional astronomy population and the associated student populace. We consider both domestic comparisons across different subject areas and international comparisons to other astronomy communities.

2.1 Domestic Comparisons: Undergraduate Enrollment Evolution

We first put in context overall enrollment growth in the undergraduate sector from 2001-2010. Using Statistics Canada data, student enrollment across all fields and at all levels grew by 41% (4.5% annually). At the graduate level specifically, the growth was even larger, reaching 56% (6% annually) according to CAUT data[4]. The annual growth rates across the sciences are: Biology 6%, Chemistry 8%, Physics 3% and Astronomy 2% (see Annex 2, Table A2-2). Notably, at the undergraduate level, growth in

[4] See table Annex 2-1 for a summary of overall undergraduate enrollment data.

Chemistry and Biology is outpacing that in Physics and Astronomy, which are both slightly below the average 4.5% growth across all fields.

In terms of metrics of the quality of undergraduate education in astronomy, we can use interpolated data from ACURA surveys along with the CAUT undergraduate enrollment numbers to calculate the fraction of undergraduates involved in research. Since 2002 the percentage of astronomy undergraduates participating in research has grown from 35% to almost 60%, corresponding to an annual increase of 4%. Given that at a number of institutions all students are now graduating in the honours stream it is quite possible that this percentage will continue to rise.

Overall student numbers differ significantly across the sciences, the ratios for Astronomy to Physics to Chemistry to Biology are 1:9:19:98. Clearly, Biology is overwhelming popular as an undergraduate degree, which is unsurprising given its role as a feeder program for numerous health-related programs. Overall, Astronomy is about 1/9 the size of Physics, which is expected given that many Astronomy graduate students choose to specialize in physics at the undergraduate level.

2.2 Domestic Comparisons: Graduate Enrollment Evolution

Overall enrollment across all types of graduate programs averaged a growth rate of over 5% for the decade. We find (based upon data provided in Table A2-3) that the annual growth rates for the sciences are: Biology 7%, Chemistry 5%, Physics 10% and Astronomy 6%. The Physics growth rate appears to be an outlier and is likely due to the CAUT survey missing data in the period 2002-2004. For the remaining three subject areas the growth rates are very consistent – between 5-7%, in rough accord with the overall graduate enrollment growths.

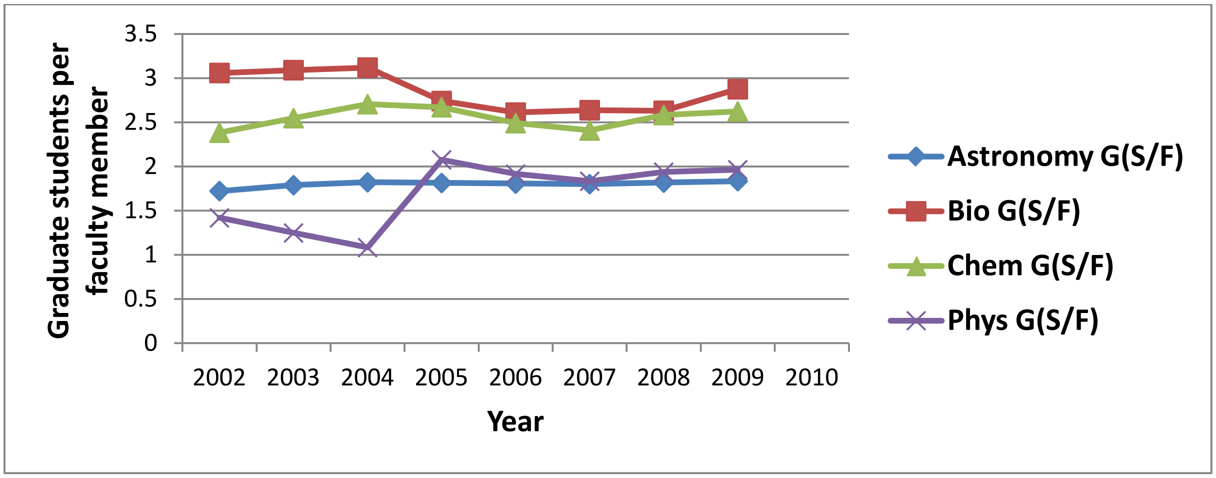
What is particularly different at the graduate level is the ratio of enrollments between subject areas. While at the undergraduate level Biology is overwhelmingly dominant, the situation is very different at the graduate level. Based upon ACURA and CAUT data the ratios between Astronomy, Physics, Chemistry and Biology are 1:6:8:12, as compared with ratios 1:9:19:98 at the undergraduate level. This indicates that students of Physics and Astronomy are more likely to enter into graduate school than students in Chemistry or Biology.

2.3 Domestic Comparisons: Faculty Complement Evolution

The significant growth in student numbers at the graduate level is likely to have translated into growth in the faculty complement. While funding is an issue, by and large time is the primary limiter on the success of graduate supervision. Analysis of CAUT and ACURA data (see Table A2-4) shows that faculty complements are growing on per annum basis as follows: Biology 8%, Chemistry 4%, Physics 3% and Astronomy 5%. All subjects maintain growth roughly in proportion to the increases in graduate enrollment.

These numbers suggest that faculty complements are strongly determined by a roughly constant graduate student to faculty ratio within a given subject area. Hence, in Figure 2-1, we plot the ratio of graduate students to faculty numbers across all the subject areas (data summarized in Table A2-5). The ratios are quite similar across all subject fields, with Biology (mean 2.84) and Chemistry (mean 2.55) averaging over 2.5 graduate students per faculty, and Physics (mean 1.64) and Astronomy (mean 1.80) averaging slightly under two. We again note that the 2002-2004 data for Physics may possibly be suspect, although data from 2005 onwards is more consistent (mean 1.94 compared to 1.64). However, overall these data are supportive of the original hypothesis that increased graduate enrollment is fuelling an increase in faculty numbers.

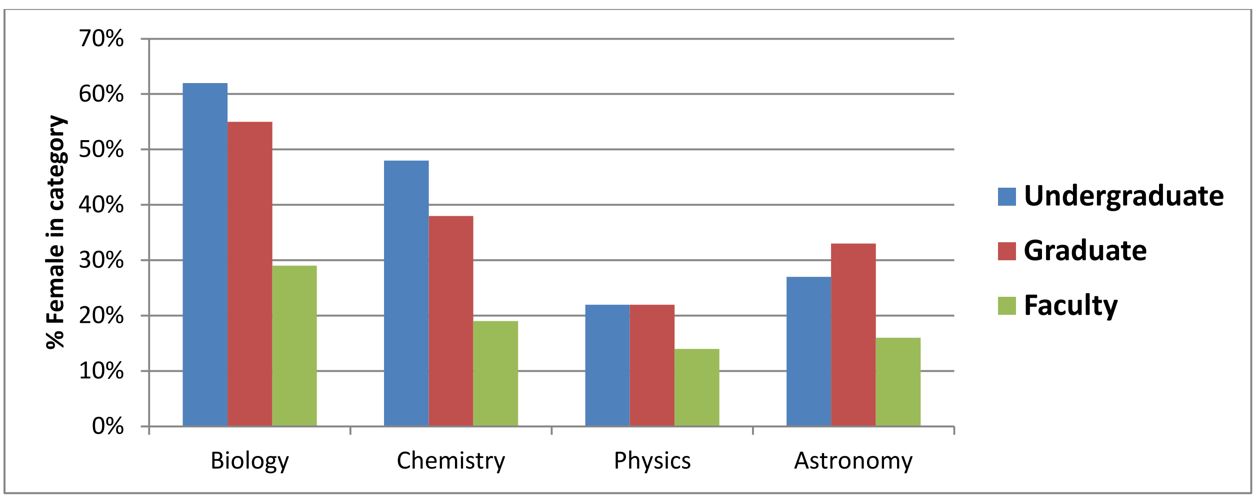
Figure 2-1: Graduate student to faculty ratios for Biology, Chemistry, Physics and Astronomy



2.4 Domestic Comparisons: Participation of Women in the Sciences

Using CAUT data we can look at the percentage of women in the different subject fields from undergraduate through to faculty. It is widely known that there is comparatively low participation of women in Physics and Astronomy, and hence it is important to quantify current values and trends.

Figure 2-2: Participation of women in the sciences at undergraduate, graduate and faculty levels



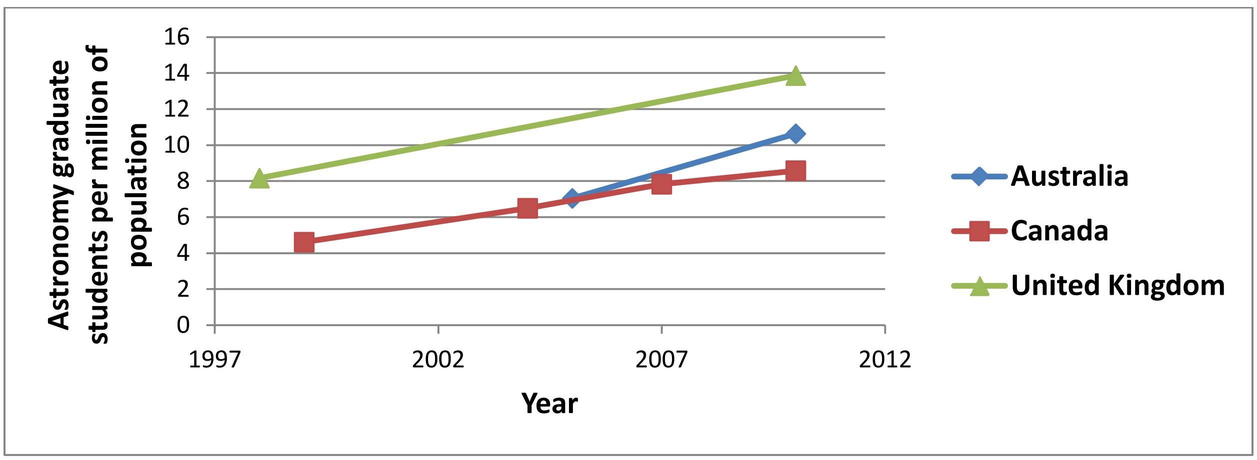
Astronomy clearly has slightly higher female participation than Physics, but still has lower numbers than Chemistry and Biology. Percentages at the faculty level remain low, but historical trends and the comparatively large residence time of faculty in a given position means that these numbers are changing slowly. We note that there are at least two universities in Canada (McMaster and Western) that have astronomy groups with close to 50% female participation at the faculty level.

In addition to the numbers presented here we have mined the data from a 2010 LRP survey of PhD students from 1990-2010. The number of female PhD graduates in Astronomy doubled from 12% in the 1990-2000 decade to 24% in the 2000-2010 decade. This growth is also consistent with student membership in CASCA which has now reached 46% female. All of these numbers strongly suggest that female participation in astronomy will continue to grow over the coming decade.

2.5 International Comparisons: Astronomy Graduate Enrollment Evolution and Sizes

Before presenting data in this section it is important to emphasize the comparative difficulty in providing comparisons from one country to another. Unless a country undertakes regular demographic surveys it is virtually impossible to assemble accurate statistics, and indeed some communities, most notably the US, are so large that only gross statistical classifiers are given. Hence in what follows we have restricted comparisons of Canada to countries that do undergo regular demographic surveys, namely the United Kingdom and Australia.

Figure 2-3: Graduate student growth in Astronomy: UK, Australia and Canada



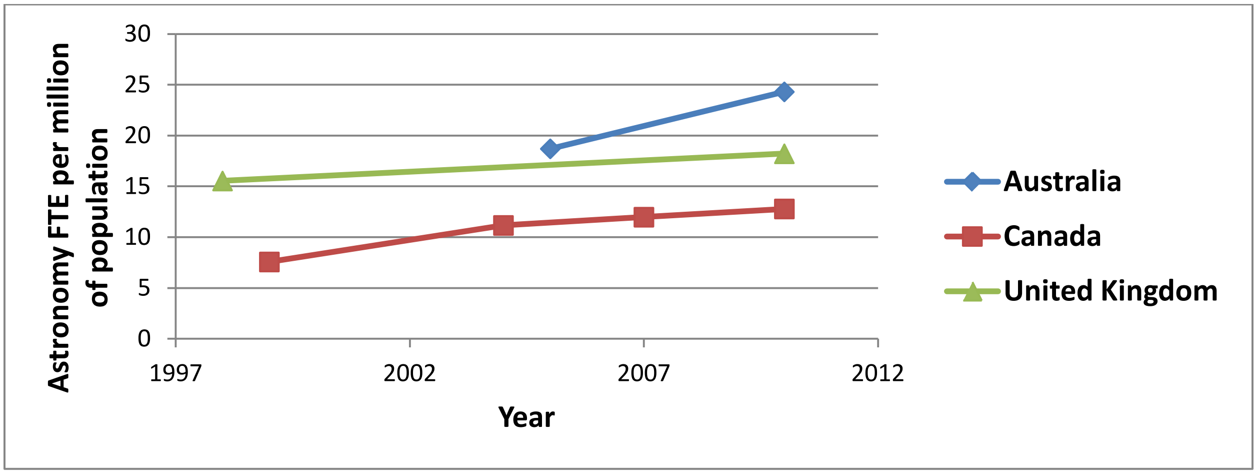
In Figure 2-3 we compare normalized graduate student populations in the UK, Australia and Canada with the population normalizations being Australia 22.3 million, UK 62.7 million and Canada 34.5 million. In Australia, the growth rate is over 10% per annum for the last 5 years, and almost 6% for the UK in the past decade. The 6% growth observed in Canada over the last decade leaves the actual population sizes at 2010 as 237 (Aus), 269 (Can) and 869 (UK) (see Table A2-7). Note that Canadian figures include both MSc and PhD students while the UK and Australia figures are essentially all PhDs. Normalizing by a CAUT (2010) statistic of 68% of Canadian astronomy graduate students being in PhDs, we find the normalized number of PhD students in astronomy in Canada to be 6 students per million of population.

Overall, growth in the Canadian astronomy student populace is in line with other countries but the relative size, as a function of overall population, is between 20 and 40% smaller than Australia and the UK respectively. We also likely have the lowest number of PhD students in an absolute sense.

2.6 International Comparisons: Full Time Astronomy Community Evolution and Sizes

We next consider the relative sizes of the normalized full time astronomy communities in Canada, Australia and the United Kingdom. These figures include faculty and post-doctoral researchers, as well as technical support staff (notably in Canada this includes HIA related personnel). The data are again taken from the demographic surveys conducted in each country, while Canadian ACURA faculty and post-doctoral fellow counts were supplemented with figures provided by the (former) HIA.

Figure 2-4: Growth of FTEs in Astronomy: UK, Australia and Canada compared



Data for the three countries is plotted in Figure 2-4 and summarized in Table A2-8 (population normalizations as in section 2.4). The UK has the largest staff complement as of 2010, with 1142 people employed. In the decade between surveys this number has not grown significantly (974 in 1999, 1% growth rate), although there has been a significant shift in astronomy research from institutes to universities (faculty numbers have risen by 65% in a decade). Postdoctoral numbers have been comparatively static across the decade at over 400 (448 as of 2010).

Since 2005, Australia's FTE count has grown by 30% (approximately 6% per year), while in Canada measured over a decade the growth is 6%, but only 2% per annum from 2004 onwards. The number of Australian faculty is not given for 2010, but we can estimate it from the percentage of researchers in 2005 to be approximately 147. This is comparable in size to Canada's faculty complement of 160 as of 2010, which indicates Canada has far fewer technical personnel than Australia. On a population normalized basis the relative sizes of the full time communities compared to Canada are 1.42 times larger for the UK, and 1.90 times larger for Australia.

The implications of these numbers for graduate/faculty ratios as of 2010 are as follows: UK 1.6, Australia 1.6, and Canada 1.8. The numbers are clearly very close and are indicative of time constraints on supervision.

2.7 International Comparisons: Participation of Women in Astronomy

As of 2010, the fraction of women in faculty positions in Australia is 22% (no student numbers were given). In the UK the fraction is 14% at the faculty level and 34% within the graduate student population. These numbers are broadly similar to the Canadian values of 16% and 33% respectively. Overall, the participation of women in astronomy in Canada appears to be broadly consistent with other countries.

2.8 Demographics takeaway: Demographic Changes over the Past Decade are Global

We have shown that the growth observed in Astronomy across all levels, from student to faculty, is in broad agreement with the general increase in size of the post-secondary sector. The numbers of faculty and students appear to be strongly tied together by a roughly constant graduate student to faculty ratio. This is also true for Biology, Chemistry and Physics.

Similar trends in growth have been observed in both the UK and Australia. Indeed both these two countries exhibit growth that in some cases considerably outstrips that in Canada (for example, the recent growth the Australian PhD contingent), while at the same time having larger communities on a population normalized basis. While the UK and Australia have larger student populations in astronomy, at least relative to the overall population of the respective countries, the graduate student to faculty ratios are very close to those in Canada.

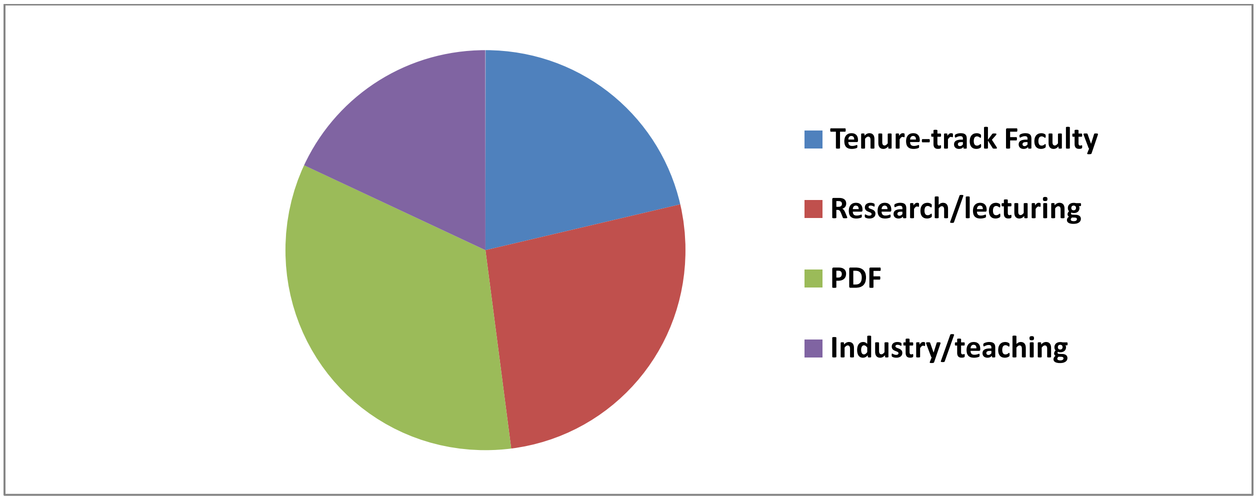
It is, however, worth noting that in many departments the funding of graduate students is entirely dependent on the availability of funds via NSERC Discovery Grants. Looking to the future, decreased support in this area has the potential to strongly impact graduate training. In Annex 2-C, we have collected data that outlines how student costs are becoming an increasingly large component of NSERC Discovery Grants.

2.9 HQP Outcomes: Destinations of PhD graduates

Extensive data on the employment data of PhD graduate students was compiled as part of the LRP planning exercise. In Figure 2-5 (see also Table A2-9) we show the employment categories of 244 (out of 257, i.e. 95% complete) astronomy PhD graduates for the 2000-2010 decade. For this initial summary we consider four distinct streams, industry/teaching (including the financial sector, software development, high school teaching and medicine), research/lecturing, which contains staff employed at research institutes and staff astronomers at observatories, and lastly tenure track which includes universities, colleges, CEGEPs.

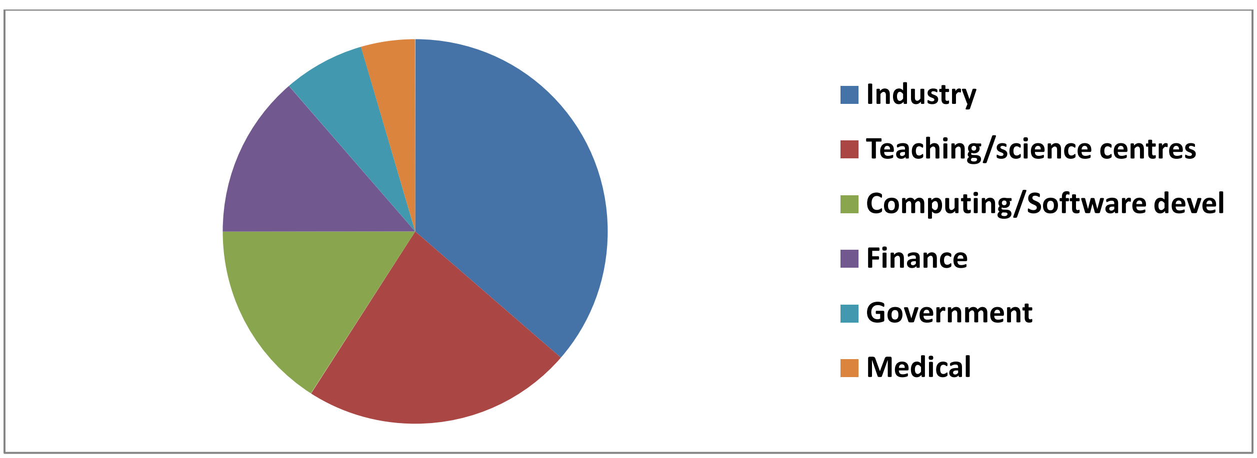
Both tenure-track outcomes and industry/teaching represent about 1/5 of the total. While PDF employment is the largest group (approximately 1/3) it's worth emphasizing that this is a transitory position. This large number could be slightly biased by an increasing number of students graduating at the end of the decade. Roughly 1 in 4 students are found in the research/lecturing group.

Figure 2-5: Distribution of astronomy PhD graduates' (1990-2010) employment as of 2010



In Figure 2-6 we next breakdown the industry/teaching category to examine outcomes of these individuals. Well over 1/3 of the PhDs in this category have transitioned into industrial positions, whilst almost 1/4 end up in teaching. Both finance (1 in 6) and computing/software development (1 in 7) continue to be strong employers of astronomy PhDs (unsurprising given the quantitative skills learnt as part of an astronomy PhD). Medicine surprisingly comes out quite low at 1 in 20. It is notable that a number of students that have MSc's transitioned into medical imaging (for example, through the Robarts Research Insitute at Western University) although we do not have quantitative data on these numbers.

Figure 2-6: Subdivision of the industry/teaching category



2.10 HQP: Responses to ACURA Questionnaire on Entrepreneurial Career Outcomes

In collaboration with Neil Rowlands of Com Dev International, ACURA prepared a questionnaire aimed at successful individuals that have transitioned out of astronomy and into industrial careers. Specifically, the focus of the questionnaire (see Annex 2-B) was to uncover views on the transferability of skills and technologies from astronomy into the wider technology sphere, as well as probing individual motivations. Individuals were identified through a request to CASCA members, and ACURA received nine testimonials in total (reproduced in full in Annex 2-B). Seven responses answered questions directly, while two provided their own personalized responses ([redacted]).

[In order to respect the privacy of the responding individuals, their names and responses are redacted or omitted from this version of the report. They are included only in the version submitted to the National Research Council, for which permissions were obtained.]

Name	Company	Web address
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	
[redacted]	[redacted]	[redacted]
	[redacted]	

Of the names listed here, [redacted] have all directly contributed to the formation of companies or have developed patented technologies. We thus categorize these individuals as entrepreneurs. We note that [redacted] runs a successful company based upon astronomy education rather than technology transfer.

The following discussion distills the extensive responses to look at three key issues: motivation, transferrable skills, and technology experiences. We emphasize that far more detail and nuance can be obtained from reading the testimonials in full.

2.10.1 Motivations*:*

Five of seven respondents note that their motivations for studying astronomy were related to curiosity about the universe. The response of [redacted] encapsulates the views of many:

“[redacted]

Intriguingly, 2 of 7 respondents cited astronomy as a challenging avenue to apply their undergraduate training in optical or electronic engineering. Overall, these numbers and the testimonials are consistent with much thinking on motivation in successful individuals (e.g. as collected in the book “Drive” by Daniel Pink and noted by members of the Conference Board of Canada). Namely that, in fields where extensive creativity and problem solving are required, the strongest motivational factors are internal rather than external.

2.10.2 Transferrable skills*:*

Four of seven respondents cited their experiences with, or helping to develop, high technologies as one of the key transferrable skills (we address specific technologies in the next section). Two more responded that mathematical modeling, and notably signal analysis, was important to their entrepreneurial success, and hand in hand with this skill, computer literacy was noted by a number of respondents as being highly valuable. Lastly, one respondent noted that the need to find motivation from within was a valuable learning experience and one that helped shaped his entrepreneurial ventures.

The symbiotic and unpredictable nature of skill transference was noted by [redacted] who holds nine patents related to computer vision:

[redacted]

On the negative side, two respondents noted that being in academia had not made it easy to transition into a business career either due to a lack of connections or cultural viewpoints. It is worth noting that these historical attitudes are changing though, with a number of graduate research and training programs focusing on transferrable skills (e.g. project management) and emphasizing different possibilities beyond academia. Culture modification was highlighted both with the Canadian LRP and US Decadal Plan as being fundamental to the success of the community.

2.10.3 Technology experiences:

Astronomy is perhaps the ultimate remote sensing field. Five of seven respondents noted that their experiences with detector technologies had directly contributed to their career, and three respondents had set up businesses based upon the detector expertise they had developed. Moreover, in almost all cases the technology is being transferred out of astronomy into other fields. For example, [redacted] states that astronomy related purchases constitute only 30% of their business with biomedical, chemistry, industrial applications being far more dominant. [redacted] sells Tunable Filter imagers, initially developed for astronomical research, that are now used in medical imaging for profiling tumor cells (among other applications). [redacted] also sells similar technologies for security, environmental and biomedical research.

With the electronic imaging market now estimated to be worth $300B, innovation from astronomy is anticipated by many to continue to play an important and catalyzing role.

2.10.4 Testimonial of [redacted]

We end by reproducing the testimonial supplied by [redacted]

“[redacted] a spin-off from TMT with a deep impact down on earth

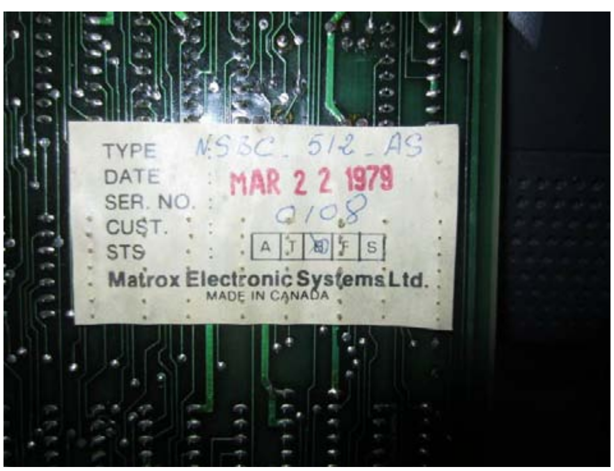
[For privacy reasons this testimonial is omitted from this version of the report.]

2.11 Astronomy Projects as Facilitators for Innovation Well Outside the Discipline

Here we look briefly at a related subject within the broad issue of HQP – the influence on innovation in industry by astronomy projects. The examples below do not comprise an exhaustive list, but they demonstrate the impact that astronomy has had in stimulating major industry activity in Canada.

Dynamic Structures Ltd (DSL, Port Coquitlam, BC) was born out of a bridge construction firm with the design and engineering contract for the 3.6-m CFH telescope enclosure in 1976. DSL has since engineered and supervised the construction of innovative enclosures for most of the world’s largest telescopes: the U.K. 4-m William Herschel telescope, the USAF Starfire 3.6-m telescope, the two 10-m Keck telescopes, the two 8-m Gemini telescopes and Japan’s 8.2-m Subaru telescope. The company is also using the expertise gained to produce entertainment rides. DSL also completed the design of the iconic enclosure for the Thirty Meter Telescope. Should Canada become a construction partner in TMT, DSL will be responsible for the enclosure, a contract generating some 800 person-years of employment in Canada and, at an estimated cost of some US$147M, the dominant in-kind Canadian contribution to the TMT project.

MATROX, a leading firm in video graphics, received an early stimulus from astronomy. The first development contract to the two sole members (Lorne Trottier and Branco Matic) in this budding Montréal firm in 1979 was for a then novel “video frame grabber card” for the Mont Mégantic 1.6-m telescope. A photo of an upgraded version of that first commercial MATROX card is seen below. MATROX has since grown into a world-size industry developing award-winning hardware and software solutions for graphics, video, and industrial imaging applications.



Daniel Langlois, a UQAM Design student, was able to develop one of his famous computer-animated movies in 1985 thanks to the Silicon Graphics IVAS system of the Université de Montréal astronomy group, which he used at night while astronomers used it in the day time. His first movie, "Tony de Peltrie (http://www.youtube.com/watch?v=munTr4vmxYE) met with enormous success. Langlois then commercialized his software under the name SoftImage and created SoftImage Inc. which Microsoft bought in 1998 and sold to Autodesk in 2004 for $30M. Daniel Langlois later founded the Excentris media complex and endowed the Daniel Langlois Foundation.

3. Support for TMT from ACURA Universities

3.1 The Value and Benefit of Astronomy as a Disciplinary Activity in Universities

In their role as developers and transmitters of knowledge, ACURA universities are engaged in astronomy for reasons well stated in a number of their Strategic Research Plans (SRPs). Extracts and references to these SRPs are in Annex 3-A. The University of Toronto's SRP perhaps expresses these reasons most comprehensively:

"Our astronomers and planetary scientists are unraveling the mysteries of our planet's formation and offering glimpses of its future. If history is any guide, whatever we discover will very likely radically affect how we think about ourselves and our place on this planet.

Observations of space are critical to advancing many key scientific issues that have long interested physicists and cosmologists: the early expanding universe, the formation of stars and galaxies, the discovery of extra-solar planets and prospects for life elsewhere in the universe. The latest instruments for space-based observations have opened up new electromagnetic windows not available to ground-based astronomy. Here on Earth, several very powerful and extremely large telescopes are currently under development and are expected to come online soon. Our global desire to explore outer space is driving a revolution in the development of new tools, systems, materials, and machines."

In a recent address to the Empire Club of Canada, David Naylor, President of the University of Toronto noted:

"Great scholars doing fundamental research can also be inspiring teachers. Ray Jayawardhana, for example, is a star-gazer. He's hunting for planets like Earth in other solar systems. What's the value of that? Can't turn that into a product or service tomorrow. Well, to me, Professor Jayawardhana's work also raises fundamental questions about humanity's place in the cosmos. RayJay and countless other colleagues spend their lives asking the questions that stretch young minds and change expectations. The resources that will win the day for Canada are the inquiring, agile, and creative minds of the next generation."

As Minister Jason Kenney also recently noted[5]: "Attracting the best and brightest young minds from around the world is key to the continued success of Canada's economy and long-term prosperity."

Not only is research in astronomy intellectually stimulating and inspiring, attracting thousands of undergraduate and hundreds of graduate students in ACURA universities, the associated challenges to design and build powerful and sensitive instruments for new telescopes also drive technological and industrial developments that see a vast realm of applications in large and sophisticated steel structures, in advanced optics, digital cameras, medical imaging, ophthalmology, GPSs, and so on.

Of the 475 professional members of the Canadian Astronomical Society working in Canada, 444 (93%) are in ACURA universities. In a very competitive environment, it is of paramount importance that Canadian astronomers have access to tools enabling forefront research. The acquisition of these tools requires today very important personnel and financial investments over long periods of time. Thus,

[5] http://www.cic.gc.ca/english/department/media/releases/2012/2012-12-28.asp

ACURA was created in 2005 to facilitate coordinated efforts between its member universities which, in collaboration with federal agencies, are responsible for planning and designing major astronomical facilities. Together with NRC, ACURA is helping to ensure that the access Canadian astronomers have historically have had to the world most powerful observatories[6] continues into the 21st century.

3.2 Astronomy and the Vision of ACURA Universities in Global Knowledge Generation

All research universities look outward to establish partnerships and international links in their drive toward excellence in their research. Indeed the term "International Relations" is frequently incorporated into the title of Vice President Research. The value of international partnerships is consistently expressed in the Strategic Research Plans (SRPs) of ACURA institutions. For example:

UBC:

"A separate International Strategy for UBC has been developed, so there is not a need to duplicate that effort in the Research Strategy. However, international partnerships are an important feature of research excellence, research collaborations are an important feature of any international strategy, and much of the research at UBC has a necessary international component. Support for international engagement will be an important component of the strategy."

Toronto:

"Faced with the high costs of appointing and enabling new faculty, as well as the escalating costs of increasingly sophisticated equipment and buildings, no government can build such strength in all of the institutions across its system. These constraints require scholars in many fields to work in large, collaborative, interdisciplinary, and often nationally or internationally networked teams."

and

"Collaborations with colleagues of the highest order at other institutions, both within Canada and internationally, can enable outstanding work right here at U of T. We will actively seek out excellent collaborators wherever we find them."

McGill:

"Bringing together leaders – regardless of discipline, background, or affiliation – can generate new ideas and approaches. At home and abroad, our faculty and students build bridges with colleagues from other leading research institutions, governments, private industry, and community-based organizations."

The strategies expressed in these brief quotes exemplify the benefits of participation in TMT which accrue from international collaboration, namely:

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[6] 1917: Dominion Astrophysical Observatory 1.8-m Plaskett telescope; 1935: David Dunlap Observatory 1.9-m telescope, 1979: Canada-France-Hawaii 3.6-m telescope; 1990: Gemini 8-m telescopes; 2020: Thirty Meter Telescope?

(a) the reduction in duplication of effort;
(b) the high cost of sophisticated equipment and buildings as a driver for large collaborations or internationally networked teams;
(c) the capacity to strengthen research at one's home institution by introduction of new ideas and approaches; and,
(d) the impact on the education and training of students.

The ideas expressed in university SRPs plus an examination of the astronomy and astrophysics activity in these SRPs shows clearly that astronomy provides one of the best examples of benefits of international collaboration to ACURA universities. In turn, TMT is perhaps one of the finest examples of collaboration in frontier international research.

3.3 Documented Support for TMT from University Administrations

ACURA universities have represented Canada's interest in TMT since the inaugural meeting of the joint project at Caltech in June 2003. They secured $15M in funding from CFI, NSERC and provincial agencies for the design and development phase of the facility. ACURA universities have committed advanced spending of funds totaling more than $1,000,000 to allow the TMT project to move forward at critical moments, and the universities have provided considerable high level legal and financial advice at no cost. In addition, ACURA institutions have provided an aggregate sum of $500 000 over four years toward the cost of the TMT Detailed Design Phase. ACURA has also expended some $300 000 from its member contributions for government and public relations efforts in support of the Long Range Plan for Canadian astronomy in a period when TMT has been the financially dominant element.

The total Canadian contributions to TMT (US$) as of Jan 31, 2013, from the Collaborative Board report is summarized in the tables below:

ACURA	13,421,187
NRC-Herzberg	17,570,681
Universities	1,098,065
Total	***32,089,933***

Year	Applicant	Project	Grantor	Total Award
2000-02	Carlberg (8 Coll.)	CFHT Renewal Options	NSERC	$396,000
2002-10	Carlberg (14 U's)	Large Optical Telescope	CFI	$10,000,000
2006-11	Carlberg (62 Coll.)	Large Optical Telescope	NSERC	$9,500,000

Note that the 2006-11 NSERC grant had a match of $500,000 composed of $240,000 (Toronto), $160,000 (UBC) and $100,000 (Victoria). A copy of the letter confirming these ACURA universities' commitment to the University of Toronto, the lead institution for that NSERC grant application, is appended as Annex 3-B.

3.4 Statements of Support for TMT from Individual Universities

As part of the process of seeking the perspectives of Canadian universities on the TMT and Canadian astronomy, ACURA requested from each institution a letter addressed to the Federal Minister of State for Science and Technology describing their views and providing support for the TMT. These letters are compiled in Annex 3-C . The general themes of these letters include the importance of astronomy in research and in the teaching curriculum within the university, its importance in outreach and public relations, and the consequent importance of access to frontier facilities such as the TMT and SKA to maintain the momentum of these activities.

3.5 TMT and Theoretical Astrophysics in Canada

Canada has strong theoretical astrophysics groups located in universities across the country. The Canadian Institute for Theoretical Astrophysics (CITA) plays a key role in uniting this community (UVic, UBC, SFU, Alberta, Waterloo, Guelph, McMaster, Queens, Toronto, Montreal, McGill, UNB, and SMU) and helping theory to be one the strongest components of Canadian astrophysics. The Perimeter Institute in Waterloo is more heavily weighted to frontier physics, but that work is deeply related to the many problems of the physics of the universe, in particular Dark Energy and Cosmic Microwave Background physics. As astrophysics has undertaken larger, more precise and more complex observational measurements, the larger teams are integrating theoretical work directly into their observational analysis.

What theorists most hope from TMT are discoveries of new astrophysics and new types of stars and galaxies. Although all the data that TMT collects will be the subject of theoretical modeling and debate, there are several areas that stand out as being rich theoretical ground: (1) understanding the first massive stars to re-ionize the universe and undergo supernovae explosions producing the first metals; (2) exploring the ideas indicating that dark energy likely varies at least a little with redshift, which needs to be mapped to as high redshifts as possible; and (3) understanding the origin of massive black holes that are now known to exist in most galaxy nuclei, and suspected to exist in some globular clusters. The aperture and diffraction limited capabilities of TMT are essential to study these highly theoretical concepts further.

Over the last two decades the integration of theoretical and computational astrophysics into large observational programs has gone from occasional to almost a necessity. Large programs absolutely require extensive simulations in order to demonstrate the technical feasibility of the measurements and that the measurements will successfully test the underlying physical models. Canada's theorists and computational astrophysicists need to have Canadian access to TMT in order that they can be integrated into these teams from the outset. Without that access they are likely to be left on the outside of some of the most important observational campaigns which can greatly diminish the excitement and relevance of their work. Probably the most prominent example of this ever growing “physics” approach is the work in the Cosmic Microwave Background, where Richard Bond in Toronto and other theorists played a profound role in making predictions of the strength of the effects that a whole series of satellites and balloon experiments were seeking to make. Those predictions first played a role in the overall strategy of how the field evolved through a series of measurements and directly affected the required precision of the measurement systems. As a result Bond, along with his students and post-doctoral fellows, were invited to join in the analysis of the results of a whole series of experiments. The power of this approach is so clear that it is changing the approach to the use of telescopes and the role of theorists and computational astrophysicists, who now are as eager as observational astronomers to have access to forefront facilities.

4. The Social Impacts of Astronomical Outreach

Investment in astronomy provides a strong return on the Canadian public's investment in the development of a knowledge economy. As the most publicly accessible physical science, astronomy provides a natural vehicle for inspiring Canadians, fostering public understanding of science, and developing the human resources that are the **critical assets in future high-tech industry.** The social impacts of astronomy are many, provided there is an effective public outreach program to stimulate these impacts. Here are some examples:

4.1 National Pride from Participation in World-Class International Projects

> *"Science leadership cultivates national pride, attracts some of the best and brightest individuals into the field, and provides crucial motivation to STEM education. ... In astronomy and astrophysics, leadership is generally achieved by the ability to make scientific discoveries that involve being "first" or by establishing dominance in a particular field. Such moments often arise when insight drives new investigations or when a new instrument or technology allows us to see some aspect of the Universe in a new way."*
>
> - National Science Foundation Portfolio Review Committee

History is full of examples of national pride being enhanced through world-class excellence in astronomy. The 16th and 17th centuries provide historical examples where rulers of enlightened states eager to enhance their reputations provided funding for individual researchers who in turn made some of the most transformative discoveries of the Renaissance. For example, the Medici family funded Galileo's research and he dedicated his most famous discoveries to them. In the 18th and 19th centuries rising European 'superpowers' used national astronomy programs to revolutionize science to enhance national reputations while yielding very practical benefits. Newton's development of the laws of motion was closely linked to precision astronomical measurements of the Moon and stars undertaken at the Royal Observatory in order to secure maritime dominance through mastery of celestial navigation. Newton's discoveries strongly enhanced Britain's towering scientific reputation and indirectly led to British leadership of the industrial revolution. In the 20th century one need look no further than the United States' efforts to maintain leadership in space science as a very visible example of strong linkage between space science, national pride, and international scientific leadership. While it is obviously too soon to identify the crowning national space science achievements of the 21st century, Canada is off to a good start: at the time of writing it is hard not to be filled with national pride by the exploits of astronaut Chris Hadfield, the first Canadian commander of the International Space Station, whose 930,000 Twitter followers provide ample evidence for strong public interest in space.

4.2 Inspiring and Enhancing Public Awareness of Science

We can point to the Hubble Telescope for compelling evidence of the uniquely strong impact of space science in reaching and inspiring young people. For example, in the United States, in any given year, educational science material from Hubble Space Telescope reaches 500,000 pre-service and in-service educators and 6.3 million students. This includes classroom-ready materials and training that supports the teaching and learning of fundamental science concepts and process skills that lie at the heart of current and future national science education standards. These materials are used in 42 of the largest 100 school districts in the US. On average, in a given month, 2.2 million science attentive members of the general public access the HST and JWST web sites reporting HST science discoveries and the technological design story of the future JWST.

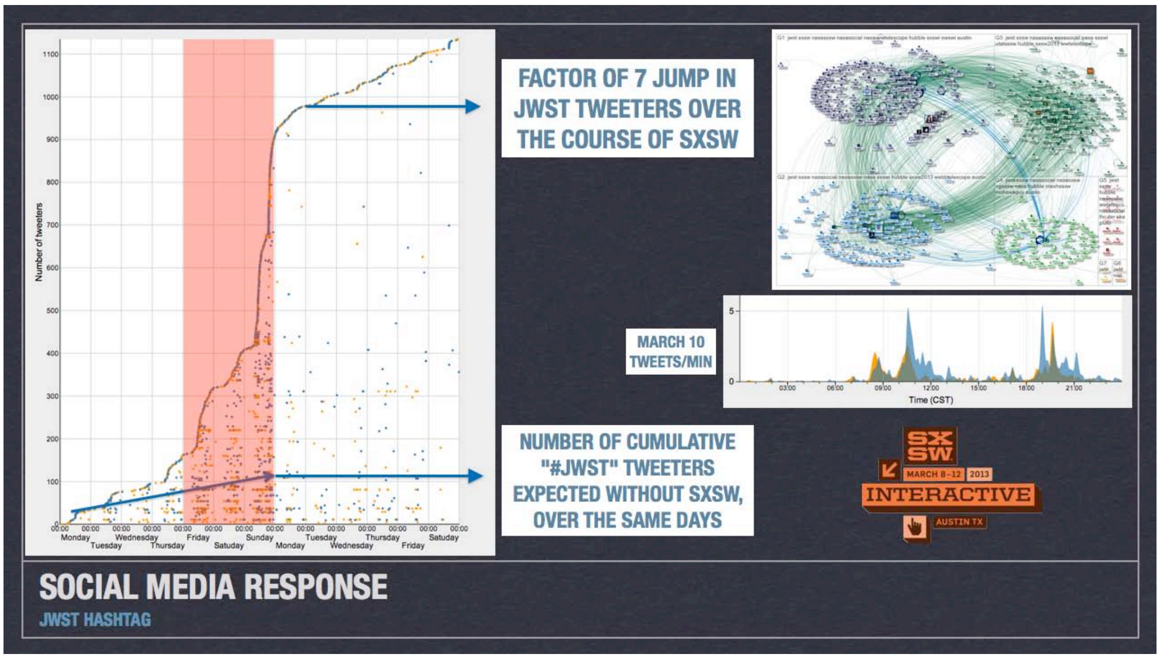


Figure 4-1: Analysis of the twitter stream with the #JWST hashtag following the South-by-Southwest conference, at which the telescope was discussed.

The Space Telescope Science Institute releases an average of one press release per week. A typical news release reaches 20-50 million readers, and it is estimated that over 100 million Americans annually see news stories originating in observations made with Hubble Space Telescope. There is a realistic potential reach of over one billion people worldwide annually. An advertising budget needed to reach an equivalent number of people is estimated to be comparable to the entire budget needed to operate the whole of CERN. Furthermore, because of their visual impact and because of the general public's strong interest in space, communication of astronomical discoveries is extraordinarily well aligned with the strengths of new media to disseminate information rapidly. A typical example is shown in Figure 4-1, which shows exponential growth the number of 'tweets' with the #JWST hashtag in response to a presentation on the James Webb Space Telescope at the recent South-by-

> *"… Astronomy does play a special role in the field of science communication. It covers a very broad area of research with instant photogenic appeal and a scale and scope that go far beyond our daily lives to stimulate the public imagination … Astronomy can lead the way for other natural sciences and be a frontrunner in science communication. It has a natural ability to fascinate and enthral, and can open young people's minds to the beauty of science."*
>
> - Lars Christensen, "Hands-on Guide for Science Communicators"

Southwest conference. There is striking consensus on the excitement of the investments we have made in this telescope: around 97% of Americans in a recent poll indicate that the Hubble Space Telescope has lived up to its promise.

Astronomy inspires and educates, but it also leads to technological spin-offs. Historical examples have already been noted, but more recently astronomical research led to the invention of Wi-Fi and to development of CCD cameras (two key technologies in a typical smart phone). In terms of specific outcomes from investment in the James Webb Space Telescope, on can already point to improved wave front-sensing optical metrology systems being used in the diagnosis of ocular diseases, to a new family of pulsed laser interferometric systems being used in aerospace and semiconductor manufacturing, and to advances infrared detector technology that have made their way into satellites for earth sensing and national defense.

4.3 Satisfying and Stimulating Public Curiosity Concerning the Deeper Questions

We live in a remarkable time, with scientists participating in explorations ranging across many fields of research. As our understanding of the universe crystallizes, we are beginning to see more overlap and synergy between formerly disparate fields of research. Astronomy, in particular, boasts some of the most remarkable discoveries of recent decades, and Canadians have a thirst for this new knowledge. Evidence for this can be seen by visiting a bookstore, or even a Shoppers Drug Mart, where no less than three popular astronomy magazines are available, several of which have circulations approaching 100,000 readers in North America. In 2009 the International Year of Astronomy generated more than two million "Galileo moments" in Canada, and recently more than seven thousand filled Varsity Stadium in Toronto for the 2012 transit of Venus.

It is no surprise that Canadians are interested in astronomy. Coupling a love of the outdoors with a long history of excellence in the subject, Canadians understand that astronomy provides an approach to some of the deepest questions that have fascinated humanity for millennia. This interest in astronomy translates naturally to a broad interest in other sciences, cementing astronomy's appeal as a conduit for greater science literacy. For instance, astronomy is of interest to chemists who use it to learn where and when the elements of the Periodic Table were created, while biologists will turn to astronomy to acquire an understanding of how the prerequisites for complex life on Earth came about. And astronomy provides the only means for testing the fundamental laws of physics on scales and in realms too extreme to be created in the laboratory, in an attempt to link the building blocks of all scientific disciplines into a single coherent understanding of the universe. Given its all-encompassing relevance to so many areas of science, is it any surprise that in the last 30 years eight astrophysicists have won Nobel Prizes? With so many prominent Canadian astrophysicists amongst the winners of top international science prizes, there is a real chance that a Canadian Nobel laureate will be joining their ranks.

> *Astronomy enriches our culture, nourishes a scientific outlook in society, and addresses important questions about humanity's place in the universe. It contributes to areas of immediate practicality, including industry, medicine, and security, and it introduces young people to quantitative reasoning and attracts them to scientific and technical careers.*
>
> - The Washington Charter

Field trip visits to CFHT have been hugely inspiring for the young Canadians I teach; the 'science highlight' of their lives, so far. Students really appreciated meeting real-life Canadian scientists, real-life astronomers interpreting data, real-life engineers digitally enhancing the photos, and real-life technologists trying to make things work smoothly. It is my estimate that over half of these students pursue science careers immediately after high school, and a very significant influence in their career choices has been seeing the Canadian telescopes in action in Hawaii.

-Brent Crich, High School Science Teacher and Department Head, Samuel Robertson Technical Secondary School, Maple Ridge, B. C.

The treasure trove of astronomical information generated by Canadian telescopes is a priceless legacy of knowledge and exploration, available to all the schools and universities in the country. Astronomical data is not only beautiful to see, but also a treasure trove of data publicly available to 'citizen scientists' in amateur organizations such as the Royal Astronomical Society of Canada and the Fédération des Astronomes Amateurs du Québec (which together boast over 10,000 members). Interested citizens can collaborate with professional astronomers (a nice example being the Galaxy Zoo project: http://galaxyzoo.org) in a joint effort to obtain a better understanding of the formation and evolution of the universe, the seeds of life, and the fundamental nature of matter and energy.

Canadian telescopes have a proud record of profound astronomical discovery (see section 1.1). The telescopes also play a role in inspiring young Canadians, who learn through outreach programs, magazines and social media about the discoveries being made with them. And seeing the telescopes in action can be a life-changing experience for students lucky enough to witness them in operation. An important goal of TMT is to further develop a vigorous outreach program to continue to foster a sense of connection between Canadians and this cutting-edge technology paid for through their tax dollars.

4.4 Role of the TMT

We are in a golden age of research and exploration, and the TMT offers an opportunity to connect these discoveries to the lives of Canadians. The TMT will stimulate the strong public interest in space science via a vigorous outreach program. It will be a flagship for Canadian leadership in Science and Technology, and will cement Canada's position as a world leader in astronomy over the coming decades. It will capitalize on Canada's investment in the James Webb Space Telescope, the successor to the Hubble Space Telescope. In short, the TMT will ensure Canadian leadership in astrophysics for generations, develop a sense of national pride in our scientific achievements, and inspire Canadians to pursue careers in science and technology.

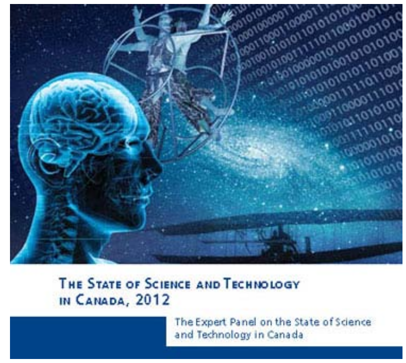
In terms of potential benefits to Canada, the MAC [CFI Multidisciplinary Assessment Committee] commented that this project ... has the potential to make significant contributions to the Canadian economy, to make fundamental contributions to research in astronomy and engineering, to significantly raise the standing of Canadian astronomy to the forefront of this field, and to contribute to public education and understanding of astronomy. The MAC further recognized that such a project would unequivocally be a source of national pride.

- CFI Multidisciplinary Assessment Committee

ANNEXES TO THE REPORT

ANNEX 1-A

Extracts from the Council of Canadian Academies Report:
The State of Science and Technology in Canada, 2012



The six research fields in which Canada excels are Clinical Medicine, Historical Studies, Information and Communication Technologies (ICT), Physics and Astronomy, Psychology and Cognitive Sciences, and Visual and Performing arts.

Three of the fields (Clinical Medicine, ICT, Physics and Astronomy) are among the five largest research enterprises in the country in terms of output of scientific papers, and the share of world publications in all fields except ICT has grown in 2005–2010 compared with 1999–2004.

Much of the nuance of Canadian S&T strength is at the sub-field level. Canada leads the world in scientific impact, as measured by bibliometrics (ARC scores), in nine sub-fields:

CCA Report 2012, Table 4.6

Sub-Fields where Canada is ranked as the Top Country in the World in terms of Average Relative Citations (ARC)

Sub-Field	ARC 2005–2010
General & Internal Medicine Clinical Medicine	3.93
Anatomy & Morphology Biomedical Research	2.38
Dermatology & Venereal Diseases Clinical Medicine	2.24
Astronomy & Astrophysics	1.86
Nuclear & Particles Physics	1.76
Classics Historical Studies	1.74
Zoology Biology	1.48
Business & Management Economics & Business	1.38
Criminology Social Sciences	1.37

ANNEX 1-B

Extracts from "Astronomy in Canada", Hickling, Arthurs & Low report to NRC, May 2011

With a history that reaches back over a century, Canadian astronomy has arisen to become one of the country's research success stories. As this study finds, its successes are indeed notable, particularly in the context of the highly competitive, and rapidly evolving international research environment in which astronomy operates. Such successes include a world renowned research community that has been recognized through numerous top awards and whose work has become among the most highly cited astronomy research in the world; an internationally recognized capability for developing pioneering astronomy technologies; and not least, a reputation for being a leading contributor and partner to some of the most influential observatories.

Today, however, the costs of next generation facilities are greater still and at the outer reaches of affordability even with international partnerships. Yet without having access to these next generation facilities, the Canadian astronomy community risks losing its capacity to push the frontiers of knowledge, and with it, its international standing and reputation for excellence. Indeed, because of the pace of technological advancement in recent years, the improvements in new telescope capabilities are significant enough that those countries which opt out of these ventures risk being marginalized at the very time when astronomy stands to make its greatest advances. In 2009, Canadian astronomy received some $86 million in support, most of which (~83%) is directed towards infrastructure. NRC-HIA and CSA are the largest funders, accounting for 80% of total expenditures, almost all of which is for the development and operation of facilities. With this support, Canadian astronomers have been able to directly access 10 facilities since 1990, totalling approximately $175 million in investments. By most measures, however, these investments are below the average of Canada's peer group of countries. As a percent of gross domestic product (GDP), five countries – the United Kingdom (UK), Italy, France, Germany and the United States (US), – spend at least twice that of Canada. In operations support alone, these same countries spend four times that of Canada.

Through a detailed economic modelling exercise, we estimate the benefit-to-cost ratio to be almost one. This is based on an estimate of total costs attributable to Gemini and ALMA of $237 million (2011 dollars), an expenditure that results in total economic benefits to Canada of $222 million (2011 dollars). In summary, Canada's participation in these international telescope ventures has been about cost neutral. Overall, therefore, the expenses incurred by the Canadian government for these two observatories are approximately equal to the quantifiable economic impacts for the country, which are in addition to the notable unquantifiable social benefits.

ANNEX 2-A

Tables for Section 2 – Highly Qualified Personnel

Table A2-1: Statistics Canada and CAUT data compiled for student enrollments

Year	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10
Total Students*	851157	887244	936390	993711	1021500	1050057	1066770	1072902	1114794	1203774
Relative 2000/01	1.00	1.04	1.10	1.17	1.20	1.23	1.25	1.26	1.31	1.41
Total Canadian**	805422	834594	876360	923523	945021	969183	984945	989274	1027707	1105920
Relative 2000/01	1.00	1.04	1.09	1.15	1.17	1.20	1.22	1.23	1.28	1.37
Graduate FTEs	94857	96842	N/A	113092	117967.9	123264	125500	134415	139682	147906
Relative 2000/01	1.00	1.02	N/A	1.19	1.24	1.30	1.32	1.42	1.47	1.56

*Total students = sum of all students enrolled in all programs, at all levels including both part-time and full time.

**Total Canadian = as for total students, but restricted only to Canadians.

***Graduate FTEs = Number of graduate students written in terms of full time equivalent students (includes all nationalities). The 2002/03 data is not provided in the CAUT Almanac for that particular year.

Table A2-2: CAUT counts for undergraduate enrollments in (general) Biology, Chemistry, Physics and Astronomy.

Year	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Bio. Students	19058	20821.5	22585	24444	24595	25795	25823	27191
Chem. Students	3365	3888.5	4412	4910	5030	5325	5416	5229
Phys. Students	2145	2325.5	2506	2583	2669	2712	2619	2609
Astr. Students	237	247	257	252	253	270	285	278

2010 data have not been given in the latest almanac.

Table A2-3: CAUT (and ACURA) counts for graduate enrollments in (general) Biology, Chemistry, Physics and Astronomy.

Year	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Bio. Students	2422	2573	2723	2409	2787	2959	3188	3587
Chem. Students	1761	1920	2078	2091	2189	2174	2394	2432
Phys. Students	997	888	779	1519	1522	1507	1632	1702
Astr. (ACURA) Students	198	211	224	239	255	270	279	287

Shaded cells are linearly interpolated based upon ACURA surveys in 1999, 2004, 2007 and 2010; the remainder of the data are taken from CAUT almanacs.

Table A2-4: CAUT (and ACURA) counts for faculty in Biology, Chemistry, Physics and Astronomy.

Year	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Bio. Faculty	792	832.5	873	879	1068	1122	1212	1248
Chem. Faculty	739	754	768	783	879	903	927	927
Phys. Faculty	703	712	720	732	795	822	843	867
Astr. (ACURA) Faculty	115	118	123	132	141	150	153	157

Shaded cells are linearly interpolated based upon ACURA surveys in 1999, 2004, 2007 and 2010; the remainder of the data are taken from CAUT almanacs.

Table A2-5: CAUT+ACURA implied graduate student/faculty ratios for Biology, Chemistry, Physics and Astronomy

Year	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09
Biology	3.06	3.09	3.12	2.74	2.61	2.64	2.63	2.87
Chemistry	2.38	2.55	2.71	2.67	2.49	2.41	2.58	2.62
Physics	1.42	1.25	1.08	2.08	1.91	1.83	1.94	1.96
Astron.	1.72	1.79	1.82	1.81	1.81	1.80	1.82	1.83

Shaded cells are linearly interpolated based upon ACURA surveys in 1999, 2004, 2007 and 2010; the remainder of the data are taken from CAUT almanacs.

Table A2-6: CAUT+ACURA (2009) data for female participation percentages across Biology, Chemistry, Physics and Astronomy

	Undergraduate	Graduate	Faculty
Biology	62%	55%	29%
Chemistry	48%	38%	19%
Physics	22%	22%	14%
Astronomy	27%	33%	16%

Table A2-7: Graduate student community sizes for the UK, Australia and Canada. Data assembled from Australian LRP and MTR planning documents and UK RAS surveys in 1998 and 2010.

	1998	1999	2004	2005	2007	2010
Australia*				157		237
Canada		159	224		270	296
United Kingdom*	512					869

*Both the UK and Australia focus primarily on PhDs and have very few MSc students.

Table A2-8: Full-time staff and faculty sizes for the UK, Australia and Canada. Data assembled from Australian LRP and MTR planning documents and UK RAS surveys in 1998 and 2010.

	1998	1999	2004	2005	2007	2010
Australia				417		542
Canada		261	385		413	441
United Kingdom	974					1142

Table A2-9: Employment outcomes for 1990-2010 PhD graduates, as given by the LRP survey.

Tenure track	Research/lecturing	Postdoctoral position	Industry/teaching
52	65	83	44

Table A2-10: Subdivision of the industry/teaching category of the PhD employment survey.

Industry	Teaching/interp.	Computing/software	Finance	Government	Medical
16	10	7	6	3	2

ANNEX 2-B

HQP Testimonials

As part of the preparation of this report, ACURA conducted a survey of CASCA members to generate a list of individuals that entered industry and have had highly successful careers, following training in astronomy. Not all individuals were supplied with contact details, and in total 18 contactable individuals were identified. The questionnaire shown below, developed in collaboration with Neil Rowlands of Com Dev International, was then sent to the 18 individuals:

Why did you to choose to study and/or do research in astronomy?

Do you feel that you gained any specific skills from your astronomy research experience that you drew upon to start your business career? Do you still make use of these skills?

Did your astronomy graduate work provide you with specific technology experience which you used to start your business career? Do you still make use of this experience in your current work?

Was there any other aspect of your background as an astronomy graduate student that has positively impacted your business career? (contacts, networking, proposal preparation, etc.?)

What did you like most about working in/studying astronomy? Were there any unanticipated surprises? Did you encounter any aspect of your current career during your graduate work?

What do you think is the most important thing people should know about astronomy research and its benefits?

Would you recommend that young people consider studying and undertaking research in astronomy? If so, why?

Any other thoughts or comments?

Responses, and the permission to use their names in the report, were provided by nine individuals, of which two provided their own letters rather than answering the above questions:

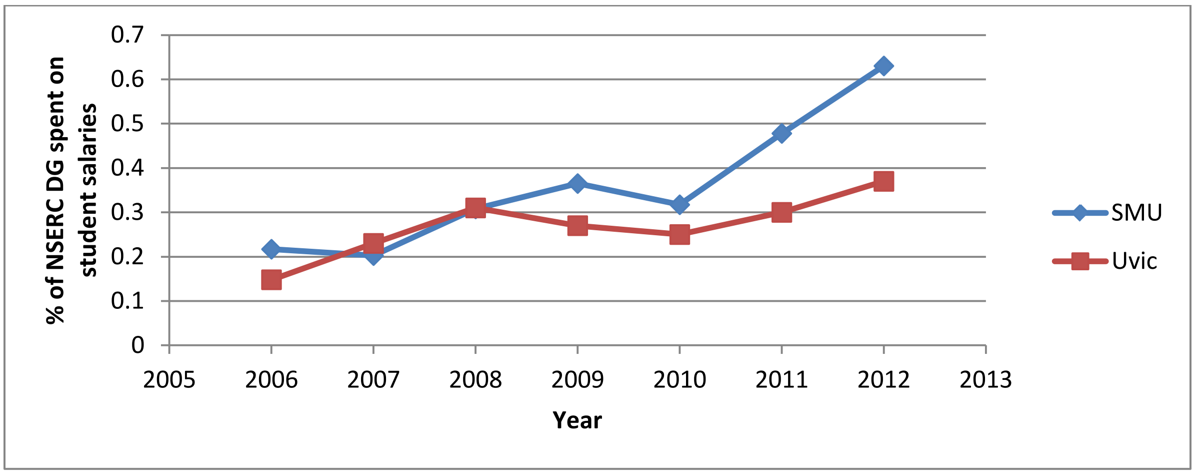
[In order to respect the privacy of the responding individuals, their names and responses are omitted from this version of the report. They are included only in the version submitted to the National Research Council, for which permissions were obtained.]

ANNEX 2-C

Challenges to HQP Funding

Although the data is challenging to assemble, we have been able to calculate the fraction of NSERC Discovery Grant (DG) funding that is used to support students for two different departments, Saint Mary's University (SMU) and the University of Victoria (UVic).

Figure 2C-1: Percentage of NSERC DG spent on students at SMU & UVic



We plot this data in Figure 2C-1 and note that the graduate population for UVic is in the range 20-25 while for SMU the range is 12-15. Overall, since 2006, the proportion of the NSERC DG going to student support has increased from 20% to over 60% at SMU (and the three newest faculty members all put 75% or more of their DG envelope towards funding students), and from 15% to 37% at UVic. This corresponds to average annual growth rates of 6% and 3% respectively.

For the SMU data we can determine the precise reasons for changes as follows: (1) student salaries are increasing rapidly due to a number of pressures (increased importance on HQP being one, increased competition among universities being another) resulting in each student costing $3.5K more than in 2006. (2) The student population at SMU has grown by 30% since 2006 (in broad agreement with overall growth levels elsewhere). Taken together these two factors have led to a doubling of the overall student support requires from NSERC grants. At the same time, the changes in the NSERC DG success rates and award amounts have seen the overall DG envelope for the department fall by 20%. The net result is that there is little room for further growth at current funding levels, and a decrease in funding would necessitate a reduction of student numbers.

Note that although the University of Toronto declined to provide precise details, they also noted there had been a 20% increase in the percentage of support to students from NSERC grants over a similar period.

ANNEX 3-A

Astronomy-related Statements in Recent University Strategic Research Plans

University of Toronto

"Our astronomers and planetary scientists are unraveling the mysteries of our planet's formation and offering glimpses of its future. If history is any guide, whatever we discover will very likely radically affect how we think about ourselves and our place on this planet.

Observations of space are critical to advancing many key scientific issues that have long interested physicists and cosmologists: the early expanding universe, the formation of stars and galaxies, the discovery of extra-solar planets and prospects for life elsewhere in the universe. The latest instruments for space-based observations have opened up new electromagnetic windows not available to ground-based astronomy. Here on Earth, several very powerful and extremely large telescopes are currently under development and are expected to come online soon. A new era of exploration also requires a new generation of technology, and our global desire to explore outer space is driving a revolution in the development of new tools, systems, materials, and machines. From spacecraft to satellites, rovers to biological monitoring systems, and from human life-support systems to strategies that enable long-term human space travel, we need new knowledge and new technologies to push beyond our current limitations. The advent of high-performance computing has provided an essential tool to analyze the wealth of new data that is being collected by telescopes, and has given us the ability to perform detailed computer simulations of the evolution of our solar system and galaxy. The more our knowledge of the solar system, our galaxy and the rest of the universe grows, the more we understand how the Earth formed and how life here arose. At UofT, our astronomers, astrophysicists, mathematicians and planetary scientists are world-renowned for their innovative approaches to some of the most fundamental questions about the nature of our universe.
http://www.research.utoronto.ca/about/strategic-research-plan/

University of Victoria

"Some of the most profound questions in science concern the nature of matter: What is matter made of? What holds it together? What determines its reactivity: How do properties change under different conditions? Can we control those properties to create new forms of matter and new materials? These questions pertain to systems ranging in scale from the smallest sub nuclear dimensions to the almost-unimaginably large structures in the universe. Members of the astrophysics group in the Department of Physics and Astronomy focus on the properties of extra-terrestrial matter, and are world-renowned for their computational, theoretical and observational work on the formation and evolution of galaxies, stellar structure and evolution, gravitational lensing, binary/multiple stars, and studies of asteroids and comet."
http://www.chairs-chaires.gc.ca/program-programme/srp-prs/victoria-eng.pdf

University of British Columbia

"*Origins Research* seeks to address the basic questions of existence, offering exciting challenges to UBC astronomers, mathematicians and physicists: *What is the universe made of? How did it begin and*

how will it end? How did our own solar system form? Is there life elsewhere? Seeking the answers to these and similar questions serves to pique public interest, to enhance students' appreciation of science, and to elevate Canada's international status in science and technology. UBC has considerable strength in this cluster. It is an important participant in several collaborative experiments to decipher the large-scale structure of the universe by measuring the cosmic microwave background. Strength in stellar astrophysics will also blend well with the proposed initiative in planetary astrophysics."
http://research.ubc.ca/sites/research.ubc.ca/files/uploads/documents/VPRI/UBC-research-strategy-May-2012.pdf

McGill University

One of seven broad Areas of Research Excellence: *Explore the natural environment, space, and the universe.*

"McGill researchers are part of a community that seeks to better understand the universe. Like others throughout history, McGill researchers investigate foundational questions such as: 'What are the origins of life?', 'How do we ensure the continued viability of our planet?' and 'What are we made of, how do we control it, and how can humanity benefit from it?' McGill is a major player in the rapid and extensive advance of our understanding of the natural world and its systems. This intellectual adventure has revealed the laws of physics and chemistry, the nature of life, the place of the Earth in the universe, and the evolution of our own species. Our knowledge continues to expand, with major discoveries being made every year in fields such as molecular biology, cosmology and nuclear physics."

Key areas include:

Astrophysics, Cosmology, and Subatomic Physics

Space Technology

http://www.mcgill.ca/research/sites/mcgill.ca.research/files/srp_long_version_final_1.pdf

Saint Mary's University

One of five Major Research Themes: Astronomy, Computational Sciences, and Subatomic Physics:

"Our Department of Astronomy and Physics is the regional leader in Astronomy and Subatomic Physics and an important player in these fields on the national scene. Astronomy and Physics is one of the most research intensive Departments within Saint Mary's University. The Institute for Computational Astrophysics (ICA) was formed to expand an area of expertise within the Department of Astronomy and Physics at Saint Mary's University. Created in 2001 as a Senate-approved research centre at Saint Mary's, the ICA host faculty members, Master and PhD students, and post-doctoral fellows from both within Saint Mary's and from other Universities around the world. The ICA promotes research in computational astrophysics through the research and publication activities of the individual members, by hosting visitors and colloquium speakers, and by having all its members participate in national and international conferences.

To fund and further develop research within this Major Research Theme, Saint Mary's has allocated two Canada Research Chairs, one at the Tier I level and one at the Tier II level. Saint Mary's also provides significant support to the Institute of Computational Astrophysics. Faculty members working in Astronomy, Computational Sciences, and Subatomic Physics, have been extremely successful

in funding competitions from CFI/NSRIT and NSERC. Saint Mary's has contributed significantly to these initiatives and will continue to do so."
http://www.smu.ca/webfiles/SRP-Senateapproved.pdf

Université de Montréal

« Un domaine stratégique de recherche : Le domaine de *l'astrophysique* et de *l'astronomie* est représenté par le vaste éventail des activités existantes et en développement en astrophysique et en astronomie stellaire, galactique et extragalactique. Un solide programme en instrumentation de pointe est mené, associé à une expertise poussée en techniques d'analyse numérique, en informatique, en traitement de l'information, en analyse d'images et en réseaux de communication.»
http://www.chairs-chaires.gc.ca/program-programme/srp-prs/montreal-fra.pdf

Queen's University

"SNOLAB is an international facility for astroparticle physics research, is a research institute at Queen's. Typical experiments at SNOLAB have 50 to hundreds of collaborators. These are from Canada, the US, the UK, France, Germany, Portugal, the Czech Republic and India."
http://www.queensu.ca/vpr/SRP/SRPMay2012Final.pdf (astro-particle)

Université Laval

« Un Secteur Prioritaire du thème Matériaux et technologies innovants : Le calcul de haute performance, notamment pour la modélisation en astrophysique, climatologie, aérodynamisme et hydrodynamisme. »
http://www2.ulaval.ca/fileadmin/ulaval_ca/Images/recherche/Documents/Politiques/PDR_2010-2014_fr_V1.pdf

University of Western Ontario

"Our capacity for materials characterization is set to expand as well with the planned construction of the Canadian Astromaterials Facility (CAF), providing what will be the planet's most advanced centre for the analysis of extraterrestrial material."

An Area of Research Strength at Western: Planets and Stars
http://president.uwo.ca/pdf/strategic-plan/r0806sen_annex1.pdf

ANNEX 3-B

Letter from ACURA supporting the TMT Detailed Design Phase

The following two pages show a copy of a letter confirming ACURA universities' commitment to the University of Toronto, the lead institution for an NSERC Special Research Opportunities Grant to support the Detailed Design Phase. In addition it contains a pledge to provide a contribution of $500,000 for this study from key ACURA member universities.

ASSOCIATION OF CANADIAN UNIVERSITIES FOR RESEARCH IN ASTRONOMY
ASSOCIATION CANADIENNE D'UNIVERSITÉS POUR LA RECHERCHE EN ASTRONOMIE
Département de physique, Université de Montréal, C.P. 6128, succursale Centre-Ville, Montréal H3C 3J7
téléphone : (514) 839-0179, courriel : acura@astro.umontreal.ca

26 July 2006

Professor John Challis,
Vice-President Research & Associate Provost
Simcoe Hall, Room 109
27 King's College Circle
University of Toronto
Toronto, ON M5S 1A1

Re: NSERC SRO application: *The Thirty Meter Telescope Project* (Carlberg et al.)

To Whom It May Concern:

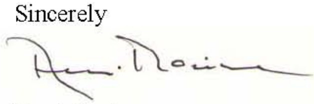
At its June 4 2006 meeting in Calgary, the Institutional Council of the Association of Canadian Universities for Research in Astronomy (ACURA) reiterated its strongest support for the participation of Canada in the Thirty Meter Telescope (TMT) Project which the above application is aimed to ensure. ACURA's purpose is to facilitate the continuing development of astronomical research in Canadian universities, whose excellence is recognized worldwide. Its efforts are currently guided by the recommendations of the *Long Range Plan for Canadian Astronomy and Astrophysics* (the LRP), access to a 30-m class telescope being the priority for ground-based optical-infrared astronomy. ACURA views TMT as an outstanding opportunity to develop university research. It is therefore proud to represent Canada in the TMT partnership with the University of California, the California Institute of Technology and the U.S. Association of Universities for Astronomy.

Extensive contributions to the design, construction, management and operation of the world class facilities selected as priorities by the LRP ensure outstanding research and training opportunities for university faculty and students. TMT will be a uniquely powerful research facility of the 21st century. The "second to none" share of TMT we aim for generates a rare and gratifying level of enthusiasm and initiative in our community reminiscent of the one the Canada-France-Hawaii Telescope project instilled thirty years ago. The on-going TMT Detailed Design Phase (DDP) has engaged scientist and engineers from many ACURA member institutions in developing concepts for novel systems. Instrumentation laboratories in support of the TMT-Canada efforts are growing at a number of universities, in keeping with a key LRP recommendation. The Canadian "imprints" on the TMT telescope, enclosure and instrumentation program are already clearly recognizable and to the great satisfaction of the partnership. The long standing collaboration between scientists and engineers in our universities and at the National Research Council's Herzberg Institute of Astrophysics is strengthened by their association on TMT projects, to the benefit of all. To formalize the relations between ACURA and NRC/HIA with respect to the TMT, a memorandum of understanding between the two parties is currently being prepared.

ACURA members have been supporting TMT since 2003 when, with the University of Toronto (UofT) as lead institution, a proposal was submitted to the Canada Foundation for Innovation that secured the initial $10M contribution from Canada to the DDP costs, with matching contributions from Ontario and British Columbia. UofT has since been managing the TMT-Canada project office while University of British Columbia and, later, Université de Montréal have supported the ACURA executive office. ACURA universities have committed advanced spending of funds totalling more than $1,000,000 to allow the TMT project to move forward at critical moments and the universities are providing considerable high level legal and financial advice at no cost. In addition, and as a contribution specific to the present SRO proposal, ACURA can assure NSERC that key member institutions will provide an aggregate sum of $500 000 over four years toward the cost of the TMT DDP.

The TMT will be a flagship of 21st century science. Our participation will bring our excellence in astronomy to new heights. ACURA is proud to represent Canada in this endeavour and excited by the opportunities it offers to its member institutions faculty, staff and students. We wish to express our strongest support for the SRO application that will allow us to proceed further along such a promising path.

Sincerely



René Racine,
Executive Director

Cc: Donald E. Brooks, Chair, ACURA Board
Pekka Sinervo, Chair, ACURA Institutional Council
Gregory G. Fahlman, Director, HIA
Raymond E. Carlberg, Canadian Project Scientist

ANNEX 3-C

Letters of Support from ACURA Universities

The following pages contain copies of letters of support for the TMT from individual ACURA universities addressed and sent to the Minister of State for Science & Technology.

[The letters of support from individual universities are not included in this version of the report. They are included only in the version submitted to the National Research Council.]