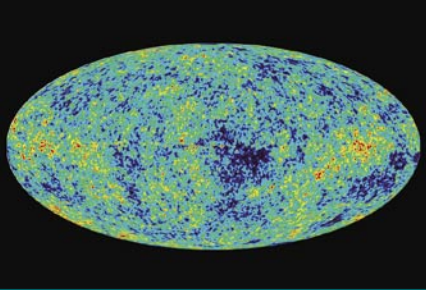
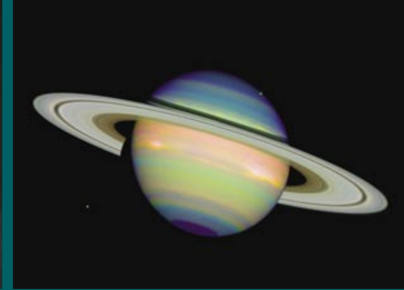


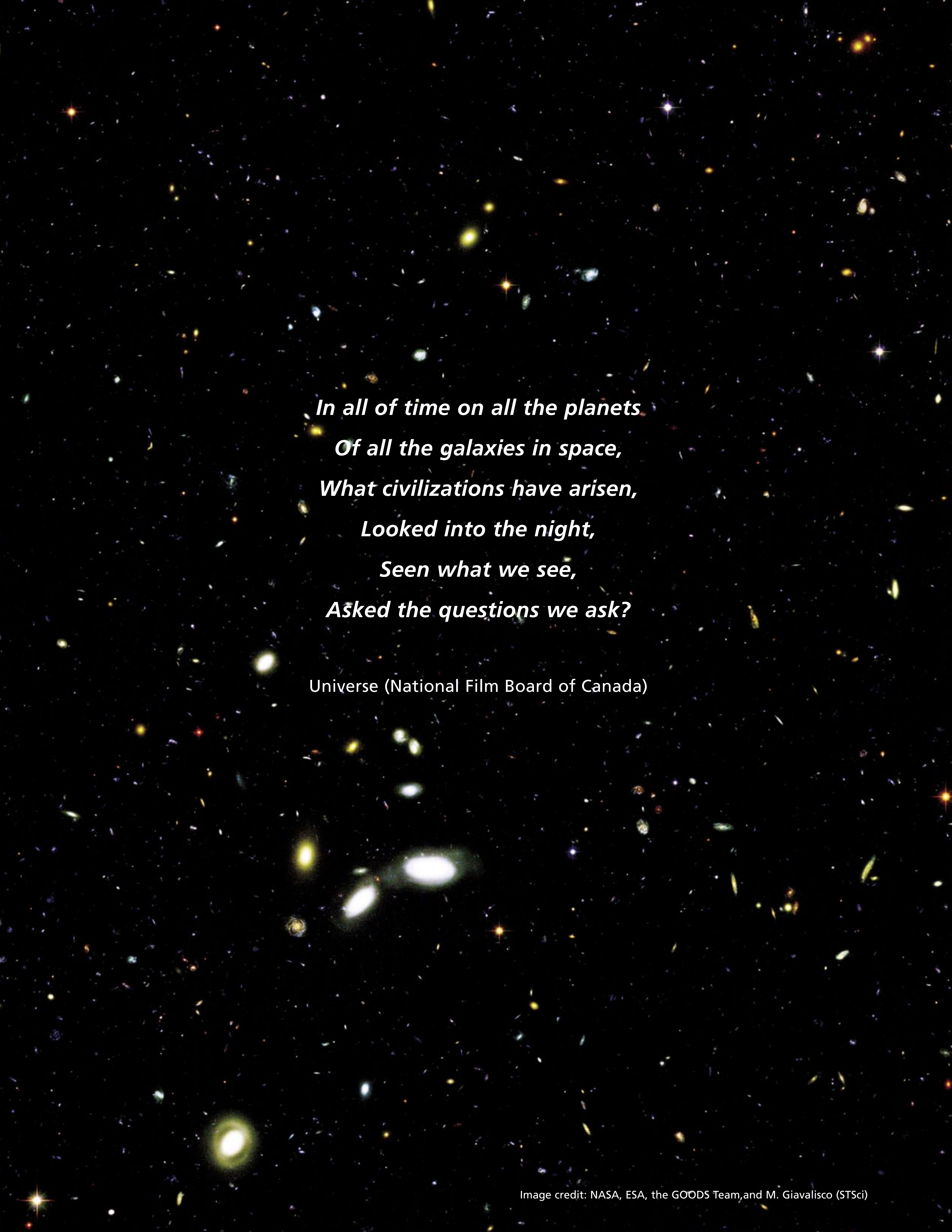



CANADIAN ASTRONOMY AND ASTROPHYSICS IN THE 21ST CENTURY

Mid-Term Review

A Report to the Canadian Astronomical Society

The Origins of Structure in the Universe



In all of time on all the planets
Of all the galaxies in space,
What civilizations have arisen,
Looked into the night,
Seen what we see,
Asked the questions we ask?

Universe (National Film Board of Canada)

Image credit: NASA, ESA, the GOODS Team,and M. Giavalisco (STSci)

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Preface

The Long Range Plan (LRP) for Canadian astronomy produced a coherent and exciting plan for the development of astronomy in Canada for the first decade of the 21st century. The LRP Panel (LRPP) wisely called for a Mid-Term Review (MTR) roughly mid-way through the implementation of the plan to review its progress and make recommendations to ensure that the LRP continues on course to achieve its goals. This document constitutes the report of the Mid-Term Review Committee (MTRC).

The LRP arose from discussions in 1998 at the Advisory Board of the Herzberg Institute of Astrophysics of the National Research Council of Canada (NRC-HIA). As the idea gained acceptance, the LRP acquired financial support from both the NRC-HIA and the Natural Sciences and Engineering Research Council of Canada (NSERC). The Canadian Astronomical Society (CASCA) reviewed the mandate of the LRP and, together with the Director General of NRC-HIA, selected the chair and worked with the latter to select the panel members. CASCA ultimately assumed the major role for the dissemination and promotion of the report.

The MTR was initiated by CASCA and, as was the case for the LRP, it was financially supported by NRC-HIA and NSERC. The MTRC gratefully acknowledges this financial support. The report also benefited from consultations with the Canadian Space Agency (CSA) and the Association of Canadian Universities for Research in Astronomy (ACURA). The MTRC thanks the many members of the astronomical community without whose input the MTR report could not have been produced. These include the many principal investigators and co-investigators who submitted detailed progress reports on their projects. We thank the staff of NRC-HIA for hosting the meeting of the MTRC with these investigators and representatives of the aforementioned organizations in April, 2004. We offer thanks also to members of the staff at the CASCA office who supervised the placement of MTR materials on the CASCA website and prepared the CASCA web forum for the exchange of views by the astronomical community. We express our appreciation to all members of CASCA who vigorously contributed their comments on this forum, and at the CASCA Annual General Meeting (AGM) held in Winnipeg in June, 2004. The many comments and views expressed had an important influence on the content of the report. We also acknowledge the work of the panel of reviewers selected by CASCA who critically read the report in its final stages, and provided valuable feedback before the report finally went to press in November, 2004.

The MTRC is grateful to Dr. Gregory Fahlman, Director General of the NRC-HIA, for critically reading several drafts of the MTR report and advising the MTRC on its content and style which led to substantial improvements in the accuracy of the report. The MTRC also thanks Dr. James Hesser, the president of CASCA, for reading the report in its final stages and for his wisdom and encouragement in helping the MTRC to produce a more informative document.

The Committee Chair offers special thanks to Dr. Ralph Pudritz, Chair of the original LRPP, for his hard work as consultant to the committee. And last but not least, the Chair offers his gratitude to the members of the MTRC for contributing their expertise with dedication and congeniality. These members include Hugh Couchman (McMaster University), Gretchen Harris (University of Waterloo, CASCA ex-officio), Victoria Kaspi (McGill University), George Mitchell (Saint Mary's University), and Harvey Richer (University of British Columbia).

E.R. Seaquist
Chair
Mid-Term Review Committee

CHAPTER 1

Introduction and Executive Summary

The LRP is a vision for modern multi-wavelength astronomy that recommends a carefully conceived plan providing for Canadian involvement in a broadly complementary set of facilities that attack some of the most fundamental problems in modern science. The LRP also demonstrated the socio-economic benefits that arise from investments in Canadian astronomy. The LRP was released in its unofficial form (English only) in November, 1999, and in its final form (both languages) at the CASCA AGM in Vancouver in May, 2000. The success in obtaining financial support for most of the initial five years of the Plan is attributable in part to the vision it projected, and in part to the vigorous efforts of the community in promoting it. Especially notable is the pivotal role of the Coalition for Canadian Astronomy (CCA), a linkage between CASCA, the universities and industry, in bringing the LRP in a compelling manner to the attention of the Federal Government.

It is now time to review the status of the LRP implementation and to make recommendations concerning the second five years, as called for in the LRP itself, to help ensure that its goals are achieved. The MTRC was struck by CASCA in February, 2004, with terms of reference provided by the CASCA Board of Directors. These terms of reference are contained in section 4.1

The LRP describes the current state of astronomy as an unprecedented golden age of discovery being driven by the advent of new technologies and powerful innovative research tools. The intervening years have demonstrated the accuracy of the LRP's assessments and have seen a quickening of the pace of LRP developments. The construction of the Atacama Large Millimeter Array (ALMA), the LRP's highest priority for ground-based telescopes, is well underway and on schedule with a strong technical role for Canada.

Canada's highest priority for space astronomy is the James Webb Space Telescope (JWST), formerly the Next Generation Space Telescope (NGST). Since 1999 the CSA has secured a major role for our scientists and industry in this unique and exciting project, as well as in other forefront international projects such as Herschel/Planck. With ALMA and JWST, great progress is being made on the first generation of World Observatories called for in the LRP. Meanwhile, projects which were on the LRP's horizon for the second decade are quickly coming into sharper focus.

The international developments bearing on the construction of large aperture optical/infrared telescopes are falling into place so quickly that Canada has already grasped the opportunity for participation in an international project to build the Thirty Meter Telescope (TMT), the world's largest optical/infrared telescope. It is the realization of one of the LRP's visions for a second-generation World Observatory, namely the Very Large Optical Telescope (VLOT). The Canada Foundation for Innovation (CFI) has awarded initial funding for Canadian participation in detailed TMT design studies.

Meanwhile, the Square Kilometer Array (SKA), a future giant radio telescope array, and ranked equally in the LRP with the VLOT as a second generation World Observatory, is moving ahead toward the selection of the technology needed to build the array. Canadian astronomers are playing a leadership role in this process, providing one of the leading designs for the SKA.

In addition to the projects described above there is a complementary need for high performance computing power. The new field of computational astrophysics is growing rapidly as astrophysical theorists now have access to powerful computers to simulate the behaviour of cosmic systems, and thus to enhance human comprehension of the universe. The considerable strength of the Canadian community in this area is driving a need for computing power at the highest levels measured on a world-wide scale.

The above initiatives were advocated by the LRP as a highly complementary set of tools, all equally essential to answer different facets of the most pressing questions in astronomy. The MTR reinforces this view. The projects currently planned for Canadian participation cover a wide array of wavebands contiguously from long radio wavelengths, near 3 metres, to the short wavelength ultraviolet near 0.3 microns. This range corresponds to a factor of 10 million in wavelength, essentially the complete spectrum except for X-rays and γ-rays. The extent and completeness of this coverage, and the uniformly high sensitivity and resolution of the proposed instruments, emphasize that all of the projects are to be viewed as part and parcel of a complete plan to pursue in the most complete way the answers to the major cosmic questions addressed.

The Canadian astronomical community has already been successful in achieving many of the goals of the first five years of the LRP, and this is in large measure attributable to Canada's worldwide stature in astronomy, convincingly documented in the LRP, and more recently evident from citations in the Thomson ISI database. Citations of Canadian papers in the category of space science, which is dominated by astronomy and astrophysics, is 39 percent above the world average, and Canada is ranked third in the world. Also, of the 159 highly cited Canadian researchers identified in the ISI database, 8 are astronomers. Canadian astronomy is thus disproportionately represented in this list of "citation laureates" when compared to the fraction of astronomers among Canadian scientists. For Canada to sustain its prominent position in world astronomy, and to foster Canadian expertise in the technology of astronomy, Canadian astronomers will need the powerful tools recommended in the LRP and to be heavily involved in their technological development.

In addition to developing the appropriate instrumentation for Canadian astronomy, the LRP and the MTR are vitally concerned with the dissemination of the successful achievements in Canadian astronomy to the public and to the students in our education system. Astronomy enjoys an ever increasing popularity with members of the public, and their curiosity about the universe needs to be satisfied by access to the exciting results from the powerful new LRP facilities. In particular, Canadians need to see and hear their own astronomers talk about the discoveries they have made with Canadian facilities.

Finally, while this report deals with comparatively large projects developed and used by many astronomers, there needs to be continuing engagement by individuals or small groups in projects at a moderate scale. Such projects encompass some of the most fundamental research in astrophysics, and are frequently required to support the research undertaken with the World Observatories. In addition, the moderate initiatives can lead to breakthroughs in both science and technology which enhance and accelerate the larger initiatives. The MTRC recognizes the need for a wide range of tools and resources and encourages moderate scale initiatives.

Executive Summary

The MTRC has examined the state of the implementation of the LRP and developed a set of recommendations which are summarized below. The recommendations for each project are accompanied by a brief summary of the project status and rationale for the recommendations. The format for the presentation of the projects and associated recommendations follows that in the LRP document. Recommendations presented as "strong" reflect a higher level of priority, and are especially important for the success of the LRP. These apply to the development of World Observatories, new instrumentation for Gemini, and to the enhancement of human resources needed to support the LRP. The highest priority in the MTR is attached to the completion of Canada's contributions to ALMA and the JWST. The highest priority for construction of a new major facility is for the VLOT/TMT. The highest priorities for moderate scale projects are the preparatory engineering studies for the VLOT/TMT and the SKA.

World Observatories: First Generation (2000-2010)

(a) The Atacama Large Millimeter Array (ALMA)

ALMA is the top priority in the LRP for ground-based astronomy, and the project is well on course with Canada's involvement through the North American Program in Radio Astronomy (NAPRA). NRC-HIA is making excellent progress on its NAPRA contributions which are the commissioning receivers at 3 mm (band 3) for ALMA and the new wideband correlator, the primary signal processor for the US Expanded Very Large Array (EVLA). Both projects are an excellent match to the internationally renowned NRC-HIA expertise in radio astronomy. The recommendations concern the financial support needed to complete our ALMA commitments and the preservation of this expertise.

The MTRC commends the NRC-HIA, its university colleagues, the Coalition for Canadian Astronomy, and the astronomy community at large for their contributions in securing a successful start to Canada's participation in ALMA, and **reaffirms** the LRPP's strong recommendation that ALMA be Canada's first priority for ground-based facilities in this decade.

The MTRC strongly recommends funding for completion of the 3 mm commissioning receivers (band 3 receivers), and that additional funds be identified for Canada's participation in the operating cost for ALMA. The completion of these commitments has the highest priority among ground-based projects considered in the MTR.

The MRTC commends NRC-HIA for its leadership in developing the 3 mm ALMA receivers and the correlator for the EVLA. These projects highlight NRC-HIA's increasing strength in radio astronomy technology, in accord with the recommendation by the LRP, and **the MTRC recommends** that these skills be maintained to provide roles for Canada in future radio astronomy initiatives.

(b) The James Webb Space Telescope (JWST) and Canada's Space Astronomy Program

The JWST is Canada's first priority for large projects in space astronomy in this decade. Under direction of the CSA, and with strong involvement by the Canadian aerospace industry, Canada has secured a share of this project for its scientific community and for Canadian industry. This represents one of the most exciting and significant developments in the history of Canadian astronomy. The CSA is playing an increasingly essential role in supporting astronomical research in Canada, and this fact provides a strong motivation for strengthening the ties between the CSA and Canadian astronomers.

The MTRC reiterates the LRPP's strong recommendation that the JWST be Canada's highest priority for participation in a major, space-based, observatory in this decade. **The MTRC commends** the CSA for securing for Canada a share in this unique and exciting project, and **commends** NRC-HIA for securing more than Canada's proportionate share of the instrument development.

The MTRC recommends that CASCA conduct a study of the needs of Canadian astronomy in the area of space astrophysics to inform the next Long Range Plan.

The MTRC commends the CSA for hiring astronomers whose responsibilities will include an active research program at the CSA. **The MTRC further recommends**

that the ties between the CSA and the astronomical community be further strengthened by altering the membership of the JCSA to ensure broader representation by the astronomy community.

World Observatories: Second Generation (2010-2020)

(a) Square Kilometer Array (SKA)

The international SKA studies will lead to the largest centimetre-wave radio telescope array ever built, with a transformative impact on cosmology and other areas. Through NRC-HIA, Canada's principal contribution now is the development of one of the leading designs for the array elements, termed the Large Adaptive Reflector (LAR). The LAR engineering study, termed the Phase B Study, is underway but needs support to continue. Because of its radio astronomy expertise, Canada will be a leader in the SKA regardless of whether the LAR is the selected design, and it needs to consider many options for its technical contributions to the SKA as it evolves toward a full international project.

The MTRC strongly reaffirms the original LRPP recommendation that Canada position itself to play a leadership role in the international SKA initiative.

The MTRC strongly recommends that the Phase B Study, leading to a design of the Large Adaptive Reflector, be supported to ensure its successful and timely completion for the selection of the design of the SKA by the international SKA consortium. The Phase B Study should be at the highest priority level among moderate size projects.

The MTRC recommends that NRC-HIA plan to participate in the construction of prototype components of the SKA once the decision on the SKA technology has been made. This could be either an antenna element based on the LAR design, if this design is adopted by the SKA project, or other components based either on the work of the Phase B Study or on other expertise in radio astronomy instrumentation.

(b) Very Large Optical Telescope (VLOT)

International VLOT studies now underway will soon lead to the construction of the largest optical/infrared telescope in the world, setting astronomy on a new course to address the most pressing scientific issues. Canada's expertise in VLOT design and instrumentation provides a compelling case for Canadian partnership in such a project. Though the LRP envisaged that the construction of the VLOT would happen in the second decade of this century, rapid developments have led Canada to become a significant partner now in the unique TMT project. ACURA is taking the lead for Canadian participation, and will collaborate in this with NRC-HIA. The focus of the MTRC recommendation is the urgent need for project financial support.

The MTRC strongly reaffirms the original LRPP recommendation that Canada position itself to play a leadership role in an international VLOT project. The MTRC strongly endorses the TMT project as Canada's route to achieve this goal.

The MTRC strongly recommends that the Detailed Design Phase of the TMT project be supported to fulfill Canada's obligation as an equal partner. This should be at the highest priority level among moderate size projects. CFI has made an interim award, contingent on securing matching funds. It is anticipated that both the Ontario and BC governments will soon contribute matching amounts, and NRC-HIA should participate by contributing matching funds as required to ensure that this major effort proceeds as planned.

The MTRC strongly recommends that a partnership for Canada in the TMT project, equivalent to that of the other major partners, be adopted as the current highest priority for funding of the construction of a new World Observatory facility.

National and International Observatories

(a) Space-Based Observatories

The MTRC was impressed with progress toward Canadian involvement in Herschel/Planck and the strong Canadian presence in current space astronomy missions, including MOST, FUSE, ODIN and BLAST. These missions complement ground-based observations and provide Canadian astronomers with the needed access to regions of the electromagnetic spectrum unavailable from the ground.

The MTRC strongly reaffirms the LRPP's recommendation for Canadian participation in Herschel/Planck, and **commends** the CSA for its continuing commitment to Canada's participation in this and other space astronomy missions of high promise.

(b) Gemini

The twin eight metre Gemini telescopes, one in Hawaii and the other in Chile, currently provide Canada with full sky access to world leading research tools in optical/infrared astronomy. Our achievements with these telescopes are maintaining Canada's demonstrated reputation for excellence in both the astronomical science and instrument development. The recommendations focus on the international plan for transformative enhancements in instrumentation and operations to address vital new scientific questions.

The MTRC reaffirms the LRPP recommendation that Gemini should be given highest priority for ongoing operations support among our international projects. **The MTRC recommends** that Canada support the plan for Gemini to operate in a mode in which most programs are conducted under queue and service observing.

The MTRC strongly endorses the participation of Canada in providing its share of the new instrumentation required to address the forefront scientific questions of broad interest.

(c) The Canada-France-Hawaii Telescope (CFHT)

The 3.6 metre aperture CFHT is one the most productive optical/infrared telescopes in the world, and will continue to be so for several more years, as exciting new scientific results emerge from the use of its new wide field optical camera called MegaCam. This instrument plus WIRCam, a new wide field infrared camera to be installed soon, will be the primary workhorse instruments of the CFHT.

The MTRC recommends that Canada continue to participate in CFHT for as long as the science produced by its new instruments remains compelling. A redirection of CFHT support to higher priority facilities should be considered, as needed, toward the end of this decade.

(d) The James Clerk Maxwell Telescope (JCMT)

The JCMT remains the most powerful sub-mm telescope in the world. Canada's commitments to the JCMT expire in 2009, and the MTRC recommendation concerns the impact of two new powerful wide field cameras – HARP-B and especially SCUBA-2 – on the timing of the withdrawal of Canadian support from the JCMT.

The MTRC reaffirms the LRPP recommendation to phase out Canada's involvement with the JCMT as our various scientific and technical commitments are completed, and to transfer the operating support to ALMA. **The MTRC also recommends** that a final decision on when to end Canada's commitment should not be taken without a full assessment of the scientific value of SCUBA-2 on JCMT and the possible benefits of extending the term of Canada's involvement in this telescope by a few years.

Ground-Based National Observatories

(a) The Dominion Radio Astrophysical Observatory (DRAO)

The DRAO is the site of NRC-HIA's powerful aperture synthesis radio telescope that enabled the highly successful Canadian Galactic Plane Survey (CGPS). The CGPS requires modest additional LRP support to extend the survey to cover the entire Milky Way visible from DRAO.

The MTRC recommends that the previously allocated NRC LRP funding for the Canadian Galactic Plane Survey be continued at the current rate until 2007 to enable a proposed extension within the International Galactic Plane Survey program.

(b) The Dominion Astrophysical Observatory (DAO)

The DAO hosts the 1.8 metre and 1.2 metre aperture telescopes, both historic Canadian instruments. Though modest by the standards of the LRP primary initiatives, these telescopes constitute important moderate scale facilities for fundamental astronomical research and education.

The MTRC recommends that the current LRP support for the enhancement of the scientific capabilities of the DAO telescopes be continued.

People

The LRPP made strong recommendations for new research positions at NRC-HIA, for new prestigious post-doctoral level programs, for strengthening programs involving instrumentation labs in Canadian universities, and for increased grant support for Canadian university researchers. While there are successes in some of these categories, more progress needs to be made to yield the fullest benefit from the LRP facilities. In view of the earlier timeline for the construction of a VLOT and the importance of developing SKA prototype components, the MTRC believes that the original LRP recommendations on people issues were too modest, and that more research scientists will be needed.

The MRTC commends the partial fulfillment of the LRP recommendations in the acquisition of new staff positions at NRC-HIA and the introduction of a new postdoctoral fellowship program in space science announced by the CSA. **The MRTC re-affirms and re-iterates** the LRP recommendations on the building of university labs in experimental astrophysics, increased grant support for university researchers in astronomy, and the importance of building strength in research positions in both the university and government sectors of astronomy to realize the full benefit of the LRP facilities. In view of the anticipated demands for research personnel to fill the needs of the SKA development and the TMT, **the MTRC strongly recommends** that the number of NRC-HIA research positions, Herzberg Fellowships, and NSERC/CSA fellowships all be increased to ten from the six recommended in the LRP. This level should be reached before first light on the TMT. There should be commensurate increases in the numbers of university researchers in astronomy, especially in the area of instrumentation in both space and ground-based astronomy.

The MRTC recommends that ACURA, representing all Canadian universities active in astronomy, consult with CASCA and NSERC with the view to transforming the astronomy grants program to an envelope funding system. Such a system would provide allocations to facilitate the establishment of new university laboratories in experimental astrophysics and the operation of the NSERC/CSA fellowship program described in the previous recommendation.

Computation

(a) The Canadian Astronomy Data Centre (CADC) and Data Analysis

In accordance with the LRP recommendations, NRC-HIA has invested heavily in its CADC facility which provides archival storage and retrieval of the large amounts of data produced by the major observatories, including data mining tools. The CADC has now largely met the goals set out in the LRP. To meet the increasing challenges created by the rapid growth of the data volumes worldwide, it is now timely to consider how best to plan for increased effectiveness of the CADC and to ensure that Canadian scientists will have the tools to retrieve and analyze their data from LRP and other large facilities in an effective manner.

The MTRC recommends that NRC-HIA conduct a review of Canada's role in global data management and the CADC's contributions to this role, particularly in light of the new ground-based and space-based facilities such as those described in the LRP. Meanwhile, LRP support for CADC should be continued to help maintain the strengths of the existing programs.

The MTRC recommends that CASCA, through its subcommittees, conduct a review of the data retrieval and analysis requirements of all LRP facilities, and then consult with NRC-HIA and ACURA to formulate a coherent strategy to address this issue. This should precede and provide input to the review by NRC-HIA of the contributions by the CADC to Canada's role in global data management contained in the previous recommendation.

(b) High Performance Computing (HPC)

High performance computing at all levels is a vital ingredient for theoretical astrophysics, and is also important for special data processing requirements. The most critical need for Canadian theorists at this time is computing at a level within the top 20 in the world, taking all disciplines into account. The need is driven by the requirement for simulating the behaviour of exceedingly complex astrophysical systems.

The MTRC recommends that the HPC community urgently develop and implement a strategy for providing access to a cost-effective Tier 1 computing system for astrophysics, i.e. one which is competitive with the leading systems over all disciplines worldwide. The emphasis should be on covering the need for the next three-year technology cycle. The strategy must ensure access which satisfies the demand of its theoretical astrophysics community, and ensure a national leadership role for this community in computing and an international leadership role in the science achieved. Concurrently the community should engage in a cross-disciplinary dialogue with the aim of ensuring long-term sustainability for Tier I HPC.

Education and Outreach

There is strong evidence that astronomy continues to excite the public and draw the interest of our educational institutions. There has been a substantial amount of activity in education and outreach by NRC, CSA, and CASCA. The MTRC focused primarily on the LRP recommendation to allocate 1.5 percent of project funds on related outreach activity, some of which should be allocated to developing and maintaining an effective website for publicizing Canadian astronomy.

The MTRC commends both CASCA and NRC-HIA for conducting a vigorous and successful program of education and outreach and recommends, in accordance with their existing plans, that this program be maintained and expanded.

The MTRC re-iterates the need for 1.5 percent of funds for each telescope or HPC project to be directed toward related outreach activity, and **recommends** that the first priority on such funds be to establish the authoritative and visually striking website recommended by the LRPP. **The MTRC furthermore recommends** that this site be maintained by the necessary full-time outreach staff, supported from the aforementioned funds recommended in the LRP. The management of the website should involve consultation with NRC-HIA, CASCA, CSA and ACURA. CASCA should assist in identifying a mechanism for administering the needed support and in identifying the host for the website.

Expenditures and Cost Estimates

Table 1 shows the total recommended expenditures in current dollars, with no inflation, for ground-based and space-based astronomy for the period 2005-11, the time remaining in the ten year cycle of the LRP since funding began in 2002. To date, three years into the initial five year funding period of the LRP, approximately $64M has been secured from NRC and CFI to support the ground-based initiatives, mainly ALMA. New funds in the amount of $69M are urgently required for ground-based astronomy, mostly to complete studies related to the SKA, to secure Canadian partnership in the TMT, to initiate a program of enhanced instrumentation for Gemini, and to develop a new top-tier high performance astrophysics computing facility. An additional $167M is recommended for the period 2007-08 through 2011-12 to continue development of all LRP ground-based projects, bringing the total amount required (from all sources) for the seven year period 2005-06 through 2011-12 to $236M. The primary incentive for the increase over the original LRP estimates for ground-based astronomy ($164M for ten years) is the VLOT/TMT project which is on an earlier schedule than envisaged in the LRP.

The CSA has committed to date nearly $39M to support Canadian participation in space astronomy, including the JWST and Herschel/Planck missions. The CSA plans an expenditure of an additional $85M for all space-based projects by 2010, bringing the CSA total to about $124M. These figures are fully endorsed by the MTRC, and additional amounts have been added for the expanded post-doctoral fellowship and outreach programs recommended by the MTRC.

Funding and Managing Large Astronomy Facilities

The support and management of large astronomical facilities in Canada needs to be addressed. The driving force is that no single federal agency or university group is able to support the entire LRP. New funding avenues (e.g. CFI) have opened up for Canadian universities to raise the funds necessary, but the scale and long-term commitments required to participate in World Observatories requires significant cooperation among the agencies and a vision of how large facilities should be funded and managed. The formation of ACURA is a response to these new opportunities and challenges, and offers an opportunity to proceed further in building a consensus on this issue.

The MTRC recommends that ACURA, in consultation with CASCA, undertake as one of its missions to develop and review models for establishing a new structure for developing and managing large facilities for Canadian astronomy. There should also be consultation with the relevant agencies, NRC-HIA, NSERC and the CSA. Account should be taken of the need to preserve the existing strengths within Canada (e.g. NRC-HIA), and to provide flexibility for individual university researchers within or outside ACURA to pursue their own astronomy projects. One of the central issues should be a stable and effective mechanism for funding the capital and operating phases of large international astronomy projects and facilities.

Economic Impact

All LRP projects are having a strong positive impact on Canadian industry and related university training. Canadian investment in the development and construction of large international telescope facilities is mostly spent in Canada, and enhances the international competitiveness of Canadian industry both in astronomy and other areas. As noted in the LRP, investments made by Government in astronomical facilities lead to a benefit/cost ratio of about 2:1. Technology areas currently being impacted by the LRP initiatives include dynamic structures, microelectronics, photonics, and other areas within the telecommunications and aerospace industry. Examples include the fabrication of large telescope and other steel structures by AMEC Dynamic Structures Ltd. and the construction of instrumentation for the JWST by EMS Technologies Inc.

Table 1: Recommended Expenditures for the Period 2005-2011 (millions of dollars)

		Priority	Ground-based	Space-based
World Facilities	ALMA	*	22	
	SKA	*	24.5	
	VLOT/TMT	*	125	
	JWST	*		60.6
	Subtotals		171.5	**60.6**
Moderate Projects	Herschel/Planck	*		8.9
	Other space projects			15.6
	Gemini	*	21.3	
	Receiver/Correlator groups		2.0	
	DAO Telescopes		0.25	
	Subtotals		**23.6**	**24.5**
People	HIA Research Staff	*	4.3	
	Herzberg Fellowships	*	3.2	
	CSA Fellowships	*		1.5
	NSERC Fellowships	*	1.6	
	Experimental Astro Labs		4.9	
	Research grants		2.1	
	Subtotals		**16.1**	**1.5**
Computing	CVO		3.0	
	HPC		15.0	
	Equipment grants		3.5	
	Subtotals		**21.5**	
	Education & Outreach		3.0	1.3
	Totals		**235.7**	**87.9**

* indicates association with a strong recommendation.

C H A P T E R 2

History and Funding of the Long Range Plan

The LRP called for an expenditure of approximately $164M to cover the costs of a strategic and exciting complement of ground-based astronomical projects and $100M for an equally exciting complement of spaced-based projects over a ten year period. As part of the Plan, the LRPP ranked various space and ground-based astronomy projects considered as first generation World Observatories, involving large international collaborations. Among space-based initiatives this ranking led to Canadian participation in the JWST, then referred to as the NGST, as the principal priority. Canadian participation in this World Observatory is funded by the CSA, who committed US$50M for Canadian participation. To date, this is the single largest Canadian investment in astronomy, and speaks to the increasing importance of the CSA and space projects in Canadian astronomy. Indeed, the CSA was a very early supporter of the LRP. Other important partnerships in space projects include Herschel/Planck (originally named FIRST/Planck). Partnership in ALMA emerged as the principal priority for first generation ground-based initiatives. The plan also recognized that on the horizon lay new exciting second generation World Observatories such as the SKA and the VLOT. Today, Canadian astronomy has advanced several years into the implementation of the plan: the projects recommended for the first five years are underway, and the projects on the horizon for the next decade show significant signs of advancement. All indicators point to success, both scientifically and economically.

As implementation of the plan unfolded in the first year, a number of developments emerged, some unanticipated. First, in January, 2001, the LRPP updated the Plan, taking into account the lack of an international partner for the proposed wide-field eight metre telescope (WF8m). The update took into account that the US Decadal Plan, released in June, 2000, had identified a VLOT, called the Giant Segmented Mirror telescope (GSMT), as the highest priority for astronomy in the US. This development stimulated international interest in designing a large telescope and the revised plan called for the redirection of the funds intended for the WF8m to bolster the development of a VLOT. Design studies were begun immediately thereafter by NRC-HIA and Canadian industry, which led to the VLOT Project Book in 2003. This "proof of concept" study of a 20 metre aperture telescope design is widely recognized for its impact. Second, the development of SCUBA-2, a powerful imaging bolometer to replace SCUBA on the JCMT around 2006, was undertaken with the participation by Canada through a grant from the CFI International Fund. This initiative was not anticipated by the LRP, and hence was not considered. Third, NRC and the US National Science Foundation (NSF) came to an understanding that Canada would participate in ALMA through an agreement between NRC-HIA and Associated Universities Inc. (AUI) which operates the National Radio Astronomy Observatory (NRAO). This agreement, termed NAPRA, made provision for Canada to have access to all radio astronomy facilities operated by NRAO (including ALMA) through a contribution equivalent to US$30M, mostly in the form of contributed hardware. Fourth, CFI, now able to fund international partnerships in infrastructure, emerged as a new potential source of funding for the LRP. This development inspired the formation of a new organization called ACURA, comprising 21 universities with the goal of obtaining support for construction and management of large facilities.

The Federal Government, having established the CFI International Fund, requested that part of the LRP be funded through a CFI proposal. In 2001, NRC submitted a Memo to Cabinet requesting $35.9M for partial funding of the LRP. This included full support for ALMA receiver development for the first five years plus other initiatives in the LRP. Meanwhile, a group of university investigators submitted a CFI proposal on behalf of the astronomical community requesting about $30M for the support of NAPRA initiatives. The proposal included a request for paying the ALMA site fee and a correlator for the EVLA to be developed at NRC. The correlator is a custom designed and built computer that combines signals from the EVLA antennas to produce images of the observed radio sources. The CFI chose not to fund the correlator project, since most of the effort would be in NRC, but it did provide funding at about $8M for the ALMA site fee (to support site infrastructure) and some ALMA software development. Subsequently, $20M for the correlator was allocated to the NRC by the Federal Government following the strong support for the project expressed by the CCA and the astronomical community as a whole. This in turn led to the signing of an MOU on ALMA between the NRC and the NSF in June, 2003. The present status is thus that about $56M was allocated to NRC and $8M to the universities. The information campaign of the CCA and the support of the astronomical community were instrumental in achieving these successes. Though less than the $82M for the first five years advocated in the LRP report, these funds permitted a substantial start on implementing the ground-based portion of the LRP, starting in 2002.

Meanwhile, the CSA proceeded with financial commitments, based on the LRP priorities, to secure a share of the recommended international space projects.

These include the JWST, with anticipated launch date 2011, and the Herschel/Planck mission (formerly FIRST/Planck), which is planned for launch in 2007. Other international space projects include ODIN, FUSE and BLAST. In addition, the CSA supported the fully Canadian space mission MOST, which was launched in 2003 and is operating successfully. The total investment by the CSA in JWST from 2000-01 to 2004-05 is C$8.3M, with remaining planned expenditures of C$60.6M by the launch date. For Herschel/Planck, the corresponding figures are C$11.8M and C$8.9M, and for MOST, the total cost was $7.9M. Including the aforementioned as well as other CSA projects, the total cost of all Canadian investments in space astronomy between 2000 and 2010 is projected to be about C$124M.

In 2003, ACURA applied for C$125M for half of the total support needed to become a 25 percent partner, in collaboration with NRC-HIA, in the international VLOT/TMT project. The partners are the California Institute of Technology (Caltech), the University of California (UC), and the Association of Universities for Research in Astronomy (AURA). The TMT project is currently advancing rapidly with the US$35M provided to Caltech and UC by the Moore Foundation. Following the favourable peer review and laudatory assessment of the ACURA proposal, the CFI agreed on 23 July, 2004 to make an interim award of C$10M, including a required match of C$6M, to enable Canadians to begin work on the detailed design phase (DDP) of the TMT. At the time of preparing this report, efforts are underway to secure the matching funds.

CHAPTER 3

Scientific Developments

Since the completion of the LRP in 1999, there has been a further explosion in our knowledge of the universe, both on the largest and the smallest scales, and awareness of profound new mysteries. In the past few years, astronomers have discovered the existence of Dark Energy, a mysterious constituent of unknown origin, comprising approximately 70 percent of the energy of the universe that is propelling a totally unanticipated accelerating expansion of the universe itself. This must now be added to the still mysterious Dark Matter, comprising about 25 percent, and the ordinary baryonic or visible matter which comprises only about 4 percent. The nature of Dark Energy is currently one of the primary questions connected with the origin of the universe. Its discovery was made by using large optical telescopes to measure the faint light of supernovae in galaxies at cosmological distances, seen now as they existed long ago in cosmic time. These observations were used to deduce that the universe was expanding more slowly in the past than at present, and hence that the universal expansion is accelerating. By extending these observations to even fainter and more distant galaxies using the JWST and the TMT, it will be possible to measure the properties and physical nature of the cosmic Dark Energy.

The structure of the Cosmic Background Radiation (CBR) has recently been revealed on a great variety of spatial scales, largely but not exclusively through successful space missions such as the Wilkinson Microwave Anisotropy Probe (WMAP). Fluctuations in the density of material in the early universe were "imprinted" upon the structure of the CBR, and this structure will be directly observed and more thoroughly characterized by satellites such as Herschel/Planck. Observations of this kind are the key not only to understanding the origin of the universe, but to understanding the origin and evolution of its constituents – the galaxies and stars. The use of imaging bolometric detectors in the sub-mm waveband, primarily SCUBA on the JCMT, has permitted the detection of galaxies at their earliest formative stages. Large optical telescopes, as well as WMAP, may have witnessed the evidence of "first light", when radiation from the first galaxies ionized the surrounding matter in the universe. This matter remained previously neutral or un-ionized during the expansion of the universe since it cooled shortly after the “Big Bang”. The epoch of “first light” will soon be detected using radio telescopes at metre wavelengths as well, and is a prime example of the potential impact of the SKA.

On smaller and more local scales, the discovery of planets around other stars has continued unabated, with 135 extra-solar planets known as of this writing. Soon hundreds of extra-solar planets will be known. Such studies are now giving insight into the frequency of occurrence of other Solar Systems like our own and how they formed. To date, it has been possible to detect only planets mostly with masses comparable to or greater than that of Jupiter, although a few planets with the mass of Uranus and Neptune have now also been detected very close to their central stars. With increasing sensitivity and resolution possible with a new generation of telescopes, it will eventually be possible to detect earth-like planets, and possibly evidence for life on these planets. In the infrared and sub-mm, new instruments are probing the processes leading to star and planet formation in our own Milky Way. The opportunities presented in this field are currently stimulating growth in star and planet formation studies in Canada, with opportunities eagerly awaited by new faculty to use ALMA, JWST and the TMT to observe regions of star and planet formation.

Recent evidence shows that all stars form in high density regions of cold molecular gas clouds by the gravitational collapse into gaseous disks. Stars then form by accretion of gas from such disks at the same time that the process of planet formation begins within them. We can directly observe the formation of these so-called proto-stellar and proto-planetary disks with the new telescopes described in the LRP and in this review, such as ALMA, JWST and the TMT, and should see evidence of giant planets forming within them.

The largest telescopes have recently probed the very centre of our Milky Way in the infrared to observe and measure the rapid motions of stars as they orbit the dynamical centre, confirming the presence there of a black hole with a mass of several million times that of the Sun. What remains to be understood is why the presence of such a black hole has not produced an “Active Galactic Nucleus” in the centre of our Galaxy. Such activity, also responsible for the phenomenon of quasars, is widely believed to occur when interstellar gas is accreted by such a black hole. The answer to this question will require studies of the interstellar gas in the nuclear region with the highest possible resolution, such as will be possible with all of the telescopes mentioned above, particularly ALMA, the SKA, as well as the TMT and JWST.

Other important breakthroughs that have occurred are in the area of compact object physics. These include the discovery of millisecond pulsations in low mass X-ray binaries, the identification of “magnetars”, or neutron stars with exceedingly intense magnetic fields, and a binary system involving two pulsars, which will provide further tests for general relativity. The SKA will extend this work to fainter levels permitting many more examples to be studied.

These and other scientific questions are ideally suited to the suite of LRP instruments because these instruments provide enhanced sensitivity and resolution over a broad range of wavelengths compared to existing telescopes. Moreover, they are complementary, providing astronomers with a more complete picture of the phenomena than possible with each instrument alone. Thus the LRP instruments may be viewed as a "package" which together will provide the tools necessary to engage Canadians in the issues at the frontiers of astrophysics.

The scientific topics described above must also be investigated using high performance computers. The sensitivity, resolution and quantity of the data from modern telescopes demand ever increasing computer power to model the observed phenomena, which in turn leads to an understanding of the processes involved. Sophisticated models have now been produced to simulate a wide range of phenomena including proto-planetary disks and jets, the rapid changes in structure within the interiors of exploding stars, interactions and mergers among galaxies, and the growth of large scale structure in the universe leading ultimately to galaxy and star formation. Such computer simulations have rapidly become an indispensable research tool and guide to planning observations with current and future generations of telescopes. Computational astrophysicists need access now to powerful computers ranging within the world's top twenty to stay at the forefront and to fully complement the powerful observational facilities in the LRP.

Canadian astronomers are making important observational and theoretical contributions to most of the aforementioned research areas, including the nature of Dark Matter, galaxy evolution, star formation, the physics of compact objects and the content and dynamics of the Solar System. In many cases they are leading their fields, and are thus poised to continue advancing Canada's reputation in astrophysics by using the facilities being developed in the LRP.

CHAPTER 4

The Mid-Term Review

4.1 Terms of Reference

The following terms of reference are based on those given to the MTRC by the CASCA Board of Directors.

Since the LRP was launched in 2000, NRC and CSA, with strong Federal Government support, have made important commitments to achieving several LRP primary goals. These include Canadian involvement in the JWST and meeting the conditions for Canadian entry into a North American collaboration that enabled Canadian partnership in ALMA.

But the LRP is, of necessity, a ten-year plan while the incremental funds are for a maximum of five years. Not all LRP recommendations are funded and, in some cases, budgeted monies run out in March, 2005, e.g., for studies leading to Canadian partnership in projects such as the SKA and for a VLOT, both of which are strongly recommended in the LRP. Moreover, LRP funding for the first five years, 2002-06, does not cover the full amount advocated in the LRP document for this period.

Meanwhile, new factors such as the availability of CFI funds for national and international projects and the establishment of ACURA are changing the landscape for funding and managing large Canadian astronomy facilities. These new developments are timely since it is now clear that NRC-HIA is not able to cover the full scope of the LRP. The review report must project a vision which accommodates and exploits the benefits of these changes. It must recommend a course to refine and successfully complete the LRP, and to anticipate possible directions taken in the next decadal plan, whose panel is to be struck by the fall of 2008.

As a mid-course review, the present document is not intended to be as extensive or as elaborate a process as the original LRP, but it requires the same integrity, commitment to openness and involvement of Canadian astronomers. The report builds on the original LRP and will be the tool by which the community will seek funding for the next phases of the LRP. The MTRC, in consultation with the Canadian astronomical community, CSA, NRC, NSERC, ACURA and relevant industries, was requested to review progress toward the LRP goals, identify any serious implementation gaps that have emerged, and recommend strategies for the next five years. The MTRC was asked to identify areas in which little progress has been made, such as the establishment of instrument labs in universities, and how to sustain the operations of the international facilities in which Canada is, or will be, involved. The scope of the review is to incorporate all initiatives outlined in the LRP, but not to include a major revision or expansion of the plan that is inconsistent with the original goals. In conducting the review, the MTRC was asked to openly involve the community through procedures which make possible input from all members of CASCA.

The MTRC was requested to make a preliminary report available to CASCA members no later than 31 May, 2004 and to provide an opportunity for discussion of that report during the CASCA AGM 13-16 June, 2004. The MTRC was asked to submit the final version of the report by 30 September, 2004.

4.2 Implementation of the MTR

In taking its first steps, the MTRC was faced with the task of producing a timely plan with a more limited scope than the LRP itself, and whose preparation would be as open as possible to the scrutiny and participation of the Canadian astronomical community. It was decided to hold one major meeting at NRC-HIA in Victoria on 22-24 April, 2004 with invited participation by community members directly concerned with implementing aspects of the LRP. The meeting was web-cast with opportunity for live e-mail feedback. An open discussion forum was also established on the CASCA website for discussing the review based on reports from principal investigators. On the basis of the meeting discussions and the feedback from the community, the MTRC prepared a preliminary report, dated 31 May, 2004. A second open forum was then held at the CASCA AGM on 16 June, 2004 based on the preliminary report. In addition, all CASCA members were invited to provide further feedback through the CASCA website forum. Based on all of the input received by late July, 2004, a penultimate draft was produced in early October and reviewed by a panel selected by CASCA. This final step extended the final deadline for the report to early November, 2004.

The format of this chapter is similar to that in Chapter 5 (The Plan) of the LRP document, which outlines the recommendations under various topic headings. Discussion of each new facility begins with a restatement of the LRP recommendations followed by an update on the work done since LRP funding. The discussion ends with new recommendations by the MTRC.

4.3 World Observatories

World Observatories are astronomical facilities whose scale and uniqueness require the support of a substantial portion of the international community and which are often one-of-a-kind facilities. Canada is already a player in international partnerships in astronomical facilities. Our role began with the CFHT on the summit of Mauna Kea in Hawaii. Canadian successes in the development and scientific use of this facility led to an international reputation, opening the door to further partnerships such as the JCMT, operating in the sub-mm region, and Gemini, the twin eight metre optical/infrared telescopes. Canada's involvement in ground-breaking research in all of these multi-national partnerships is now providing opportunities for participation in the planning and development of new one-of-a-kind World Observatories.

The LRP divided the World Observatories into First Generation (2000-2010) and Second Generation (2010-2020). ALMA and the JWST were identified as first priorities for First Generation ground and space-based observatories respectively. The SKA and the VLOT were identified as priorities for Second Generation ground-based facilities. In discussing the status of these projects we retain these distinctions, noting however that the timelines for the onset of construction or scientific operation of these projects have shifted somewhat from estimates given in the LRP. For example the JWST launch date is now 2011, a year beyond the First Generation.

A. First generation (2000-2010)

Canada's principal contribution to ALMA is to provide the first receivers for the array antennas. This contribution is critical to ALMA's early operation and will have an important economic impact through contracts to the Canadian telecommunications industry.

(a) Atacama Large Millimeter Array (ALMA)

The LRP contains the following recommendations concerning Canadian participation in World Observatories planned for the current decade (2000-2010):

The LRPP strongly recommends that Canada should quickly join the Atacama Large Millimeter Array (ALMA) project. This should be Canada's highest priority for participation in a major ground-based observatory.

The LRPP recommends that the appropriate steps be taken to ensure the best possible route for Canada's rapid entry into ALMA. There are international deadlines that must be met if we are to be partners in this project. As one possibility, the NRC should energetically investigate the creation of strong, mutually beneficial links with the USA's National Radio Astronomical Observatory (NRAO) towards this end.

The LRPP strongly recommends the enhancement of the correlator and receiver groups, within NRC. This should be one of the highest priorities among modest size projects.

The MTRC notes with pleasure that joining ALMA, the principal priority for a new ground-based facility in the LRP, is being implemented. NRC-HIA, participating university astronomers, and the CCA are to be commended for their contributions in securing Canada's participation in this World Observatory. As outlined below, the principal contribution by Canada at this stage will be the commissioning receivers, and thus Canada's role is critical to antenna commissioning. This important role in ALMA speaks well for the international community's confidence in Canada's expertise in mm and sub-mm astronomy instrumentation. The MTRC views all of the ALMA developments in Canada as a successful start, and reiterates the LRPP view of ALMA as Canada's top priority for ground-based facilities.

The second and third recommendations were carried out through the advent of NAPRA. This agreement between NRC-HIA and NRAO was signed in 2001, and constitutes an agreement by which these two organizations will cooperate in radio astronomy. Though intended as a means for Canada to become a partner in ALMA, it guarantees access by Canada to all radio astronomy facilities operated by NRAO on the same basis as the US astronomy community for a period of ten years, or five years into the operation of the Expanded Very Large Array (EVLA), whichever is longer. Though there is now a separate agreement signed later for ALMA (see below), the major technological impact of NAPRA in Canada was the agreement that NRC-HIA provide the new correlator for the EVLA, now under development, at a cost of about C$20M.

Below, we expand upon these developments:

By means of LRP funding from the NRC and CFI, Canada is now a participant in ALMA. ALMA is structured as a 50-50 partnership between Europe and North America. Discussions are in progress to include Japan as a partner as well (see below). Canada entered ALMA as a partner of the United States. The European Southern Observatory (ESO) and NSF representatives signed a bi-lateral agreement on 26 February, 2003, thereby bringing ALMA into existence and creating an eight member Board of Directors. On 16 June, 2003, NRC and NSF signed an agreement formalizing Canadian participation on the ALMA Board, the ALMA Science Advisory Committee, and time allocation committees. According to this agreement, Canada is assigned one of the four North American seats on the Board. The agreement defines Canada's right of access to ALMA as follows: "Applications from scientists at Canadian institutes for ALMA observing time will be regarded on the same basis as applications from scientists in the United States." This agreement replaces the arrangement described in NAPRA which guaranteed Canadian access to ALMA for the period of NAPRA. Construction of the access road and workers camp began in July, 2003. All the land issues in Chile were settled by 24 February, 2004. Two competing 12 metre prototype antennas were purchased and the results of their evaluation at the VLA site in New Mexico was reported in May, 2004. One of these antennas is shown in Figure 4.1.

As of April, 2004, Japan has the funding to join ALMA at a significant level, most likely providing a compact ALMA sub-array comprising a suite of twelve 7 metre and four 12 metre antennas plus receivers for additional frequency bands and other equipment. Japan's Compact Array will add important new scientific capabilities to the base-line array being built by Europe and North America. At the time of preparation of this report, an MOU between ESO, NSF and Japan has been signed. Two additional agreements defining Japanese participation fully will be negotiated in 2005. At this time the assumption is that Japan's contributions will not affect the funding needed from Europe and North America.

Canada is making important contributions to ALMA. In 2001, Canada negotiated an agreement with NRAO specifying our construction phase contributions. These are: (1) the required band 3 (3mm) receivers for the ALMA antennas; (2) secondment of an NRC-HIA receiver expert to lead the Front-End Integrated Product Team; (3) participation in software development (2.5 FTEs over 5 years); (4) a contribution of expertise towards ALMA archive development (0.5 FTE over 5 years); (5) a one-time cash contribution towards site infrastructure development in Chile.

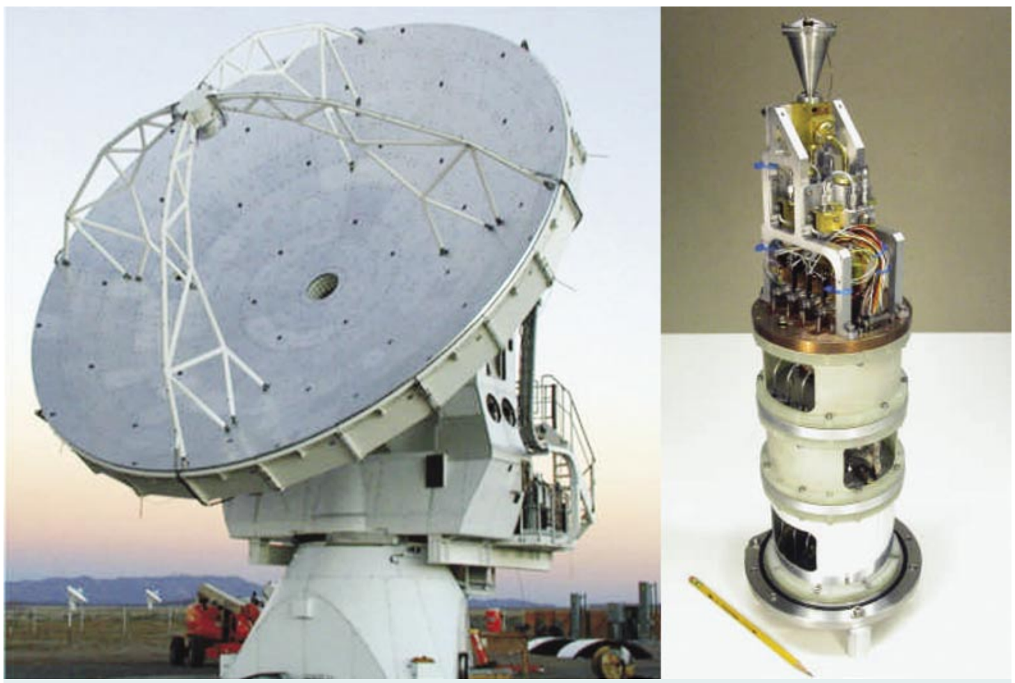

Figure 4.1: Left: Prototype Vertex 12 metre ALMA antenna under test by NRAO. Right: Prototype ALMA 3mm (band 3) receiver cartridge developed and built at NRC-HIA and undergoing thermal and mechanical tests before full performance tests in the cryostat.

Credits: NRAO/AUI/NSF (left) and NRC-HIA (right)

The allocation of the band 3 receiver project to Canada is a major achievement for NRC. These will be essential for commissioning each antenna, as well as being workhorse receivers for the science. The band 3 receivers on ALMA will be used for detection of emission from CO molecules in regions of star formation that will enable researchers to peer into the very innermost regions of nearby protostellar disks and star formation regions in galaxies that are at enormous distances from the Milky Way, and heretofore unobservable. The development and construction of these receivers represent an exciting technical challenge. They will be state-of-the-art devices with specifications not previously met by single devices operating at an absolute temperature of 4K. Consistent with LRP recommendations, the HIA receiver team is now fully staffed (approximately 14.5 FTEs involving more than 20 people). This team successfully completed a Preliminary Design Review in March, 2004, involving a panel of international experts. These developments will have an important economic impact since NRC intends to contract the construction of receivers to Canadian industry, thereby increasing Canadian strength in the area of communications electronics (see also chapter 6). Figure 4.1 shows the prototype band 3 receiver in the NRC-HIA laboratory ready to be placed in its cryostat for tests. Canada's commitment to produce one of these receivers for each of the antennas is expected to be met by Canadian industry once the prototype receiver is fully tested and accepted by ALMA.

Funding for Canada's ALMA contributions has been secured through to 2006-07. Sources of this funding are NRC ($17.4M for the band 3 receivers and support of the receiver group) and CFI ($7.93M for the site access fee and software development). The site access fee is for Canada's contribution to the site infrastructure development. The remainder of the funds are now required from NRC for HIA to complete the band 3 receiver construction and to pay for our contributions to science operations. HIA projects that its ALMA receiver construction commitments will require approximately C$12M from 2006-07 through 2011-12. Canada also has an obligation, through the MOU between NSF and NRC, to provide 7.25% of the North American share of the annual operations budget. This is estimated to be C$3-4M per year after 2012. However, early science operations will begin upon the arrival of the first three antennas, and operating costs could be required as early as 2006. Unlike a monolithic telescope, an interferometer array begins operation as soon as a few antennas are completed, so there is substantial overlap between construction and operation phases. Accordingly, the operating costs will ramp up from 2007-08 to 2011-12, requiring a total of about C$10M over this five year period. The MTRC regards both the funding for the receivers and early science operations as essential. It must be further noted here that the operating funds will be needed annually beyond 2011-12. It has been very difficult to accurately predict the final operating cost of this complex World Observatory only two years into its nine year construction period. The level of funds for the Canadian share of full operation adopted in this document is C$4M annually. The LRPP advocated that if Canada withdraws from the JCMT, staff effort and JCMT operating costs should be redirected to ALMA. The MTRC agrees with this strategy, with some qualification discussed later under JCMT. This would provide up to C$1.7M per year.

To summarize the funding situation, from 2006-07 through 2011-12, the Canadian ALMA project requires an additional C$12M to complete construction and approximately C$10M in new operating funding (slightly less if operating funds released from Canada's withdrawal from the JCMT are applied to ALMA starting in 2009).

As noted above, the EVLA correlator project is a collaboration between NRC-HIA and NRAO with the goal of improving, by an order of magnitude, key observational capabilities of the world's most powerful centimetre-wave telescope, the Very Large Array (VLA). Though not linked directly to ALMA, the EVLA correlator project is part of NAPRA. The correlator is the special purpose custom built computer that combines the signals from all the array antennas and processes them to form an image of the cosmic source observed. The new correlator provided by Canada will be one of the core elements of the EVLA's enhanced capability. The impact of the improvement will be transformative for the telescope, with roughly 35 different science areas to benefit, in some cases dramatically. Funding for the EVLA correlator is being provided directly from the Canadian Federal Government, through NRC, as an explicit component of the LRP. The amount is $C20M, running until 2007-08, and the MTRC understands this component is now completely funded.

An important element of the EVLA work is the capability of the correlator group at NRC-HIA's DRAO who developed the unique WIDAR correlator technology for this project. The main feature of the WIDAR design is its very wide bandwidth representing a breakthrough in correlator design. The UK's Jodrell Bank has contracted with NRC-HIA to build a version for their expanded MERLIN interferometer, and the design may also be relevant to the construction of the SKA. This outcome reflects NRC-HIA having followed the third LRP recommendation by providing additional support of $1.07M over the period of 2002-06 to support the correlator group. The MTRC recommends that this support be continued. In summary, the MTRC makes the following recommendations:

The MTRC commends the NRC-HIA, its university colleagues, the Coalition for Canadian Astronomy, and the astronomy community at large for their contributions in securing a successful start to Canada's participation in ALMA, and **reaffirms** the LRPP's strong recommendation that ALMA be Canada's first priority for ground-based facilities in this decade.

The MTRC strongly recommends funding for completion of the 3 mm commissioning receivers (band 3 receivers), and that additional funds be identified for Canada's participation in the operating cost for ALMA. The completion of these commitments has the highest priority among ground-based projects considered in the MTR.

The MRTC commends NRC-HIA for its leadership in developing the 3 mm ALMA receivers and the correlator for the EVLA. These projects highlight NRC-HIA's increasing strength in radio astronomy technology, in accord with the recommendation by the LRP, and the **MTRC recommends** that these skills be maintained to provide roles for Canada in future radio astronomy initiatives.

(b) The James Webb Space Telescope (JWST) and Canada's Space Astronomy Program

The JWST

The LRPP made the following recommendations concerning the JWST (formerly the NGST):

The LRPP strongly recommends that Canada, through the CSA, quickly join the Next Generation Space Telescope (NGST) project. This should be Canada's highest priority for participation in a major, space-based, observatory.

The JWST will be the most powerful and sensitive space telescope for many years, and will extend the work of the Hubble Space Telescope (HST) into the infrared. It is optimized for the region 0.6 - 28 microns, and as such, it will concentrate on scientific problems bearing, for example, on the origin and evolution of galaxies. The visible radiation from stars located within the youngest galaxies in the universe is shifted into infrared by the expansion of the universe. Consequently, the telescope will be sensitive to the light emitted from

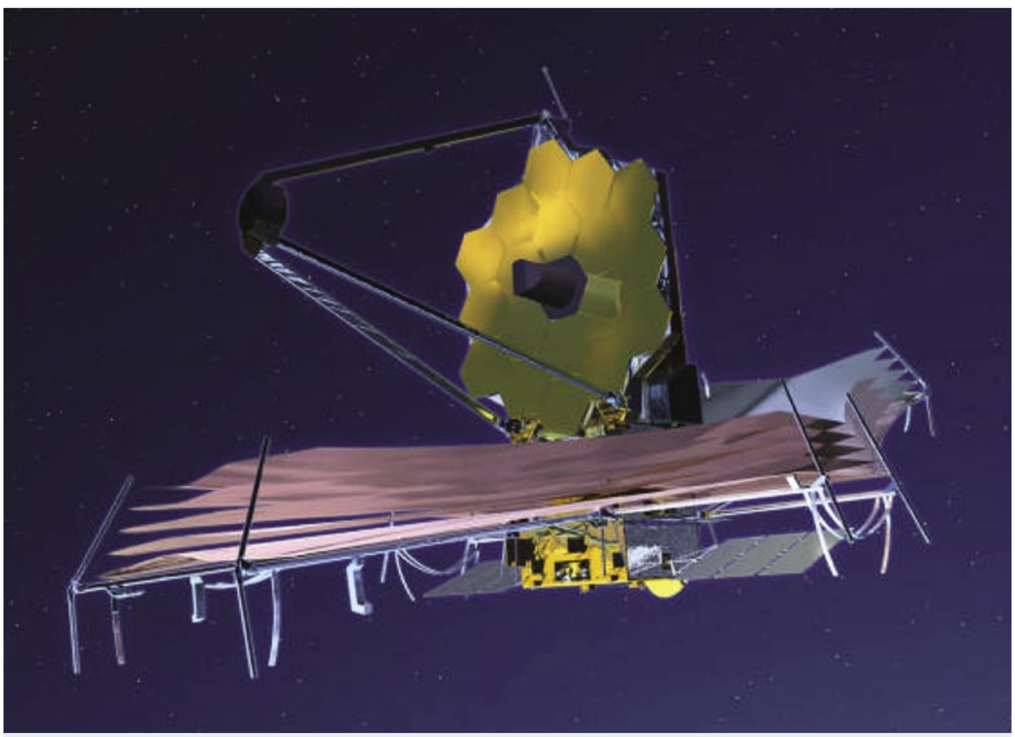

Figure 4.2: Current design concept of the JWST showing the 18 segment 6.5 metre aperture mirror. The telescope will be optimized for observations in the infrared part of the spectrum. The structure beneath the telescope is a large tennis court-size shield to protect it from the effects of solar radiation.

Credit: Northrop Grumman Space Technology galaxies ranging from the present time, for the nearest galaxies, to many billion of years ago for the most distant systems. Thus the telescope will be able to study the cosmic history of star formation with unprecedented clarity. The ground-based World Observatory telescopes such as the TMT will complement the work of the JWST by providing, for example, spectroscopic observations. Figure 4.2 shows the current design concept for this telescope.

Canada is providing the JWST with the Fine Guidance Sensor equipped with a tunable filter for narrow band imaging, recognized by the project as a contribution of major importance, and achieved through a tight collaboration among the CSA, Canadian industry and NRC-HIA.

The MTRC notes the excellent support CSA has provided for Canadian participation in the JWST and other space missions (see also section 4.4A). The total investment by the CSA in JWST from 2000-01 to 2004-05 is C$8.3M, with remaining planned expenditures of C$60.6M by the launch date. This project is by far the largest space astronomy project undertaken by the CSA. In addition, Canadian participation has benefited from allocation of considerable resources from NRC-HIA which has contributed intellectual and technical skills leading to a much greater impact by Canada than represented by its five percent share in the project.

The JWST is now a slightly less ambitious project than originally envisaged in the LRP. For budgetary reasons, some decisions were made by the international project to de-scope the project, including a reduction in aperture from 8 metres to 6.5 metres and a de-scoping of the near-infrared camera (NIRCAM). Canada is responsible for the Fine Guidance Sensor (FGS) which was redesigned following the de-scope loss of NIRCAM to include a tunable filter for imaging in narrow wavelength bands. This new design restored scientific capability to the JWST and is recognized by the project as a major achievement. The development and construction of these instruments is accomplished through a tight and effective collaboration among the CSA, Canadian industry and NRC-HIA, and is yielding an important economic impact (see chapter 6).

Canada's Space Astronomy Program

Our understanding of many important astrophysical problems has relied upon our growing ability to observe the universe from space. In virtually every area of astrophysics, from planets and stars to the CBR, we are gaining valuable and often unexpected knowledge that cannot be obtained from ground-based facilities. Without access to large regions of the spectrum accessible from both ground and space at the highest resolution and sensitivity, Canadians would be at a significant disadvantage relative to their peers in the US, Europe and Japan. It is therefore obvious that the Canadian astronomy community must continue seeking to develop deeper partnerships and more extensive scientific programs in collaboration with the CSA in the fulfillment of these broad objectives.

In the fifteen years since the foundation of the CSA, Canadian astronomers have been partners or major players in a wide variety of missions operating in wavelengths from the ultraviolet to the radio, and participation in future X-ray missions will extend this. This report has already discussed the JWST, and will discuss Herschel/Planck and several smaller missions in section 4.4A.

It is thus clear that Canada is already an important player in space astronomy. In the light of this background and the increasing importance of space astrophysics as outlined, we consider some broader issues facing Canadian space-based astrophysics.

First, the MTRC notes that in spite of the major activity in space astronomy described above and later in this chapter, Canada, on a per capita basis, spends roughly one-fiftieth that of either NASA or the European Space Agency (ESA) on space astrophysics. Also, the CSA spends roughly 3 percent of its total budget on space astronomy, in comparison to the 20 percent spent by both NASA and ESA. As Canadian astronomy continues to develop, this deficit will need to be addressed, initially by a study of the needs of Canadian astronomers in space astrophysics. The results of such an investigation would be valuable to the next planning panel in assessing the needs of Canadian astronomy overall. The study should focus on the complementary requirements of space and ground-based astronomy. Hence, the MTRC recommends that a study of the needs of Canadian astronomers in the area of space astrophysics be conducted soon. CASCA would be the appropriate body to conduct this study.

A prominent issue identified by both CASCA and the CSA is the importance of strong links between the CSA and the astronomy community. In this context, the MTRC is pleased that astronomers being hired by the CSA will be conducting their own research in addition to supporting space astronomy within the CSA. The presence of these active CSA researchers will by itself contribute to these links, as is the case between NRC-HIA and the rest of the astronomy community. In addition, the MTRC considered possible ways to further strengthen the existing ties between the Canadian astrophysics community and the CSA.

Currently, the sole official mechanism for communication between the CSA and astronomers is through the Joint Committee on Space Astronomy (JCSA), a CASCA committee whose membership is weighted toward principal and co-investigators of CSA-sponsored missions. While this communication is important and has worked well for both sides concerning specific missions, there is a need to develop effective links with the broader astronomy community as well. Broader representation by astronomers on the JCSA membership would be the preferred option. If this option is ineffective then the CSA should consider establishing an Advisory Board to advise it on broader astrophysical issues and future directions in space astronomy, rather than on individual missions. The terms of reference and representation on the Board could be similar to the HIA Advisory Board.

The MTRC makes the following recommendations concerning space astronomy:

The MTRC reiterates the LRPP's strong recommendation that the JWST be Canada's highest priority for participation in a major, space-based, observatory in this decade. **The MTRC commends** the CSA for securing for Canada a share in this unique and exciting project, and **commends** NRC-HIA for securing more than Canada's proportionate share of the instrument development.

The MTRC recommends that CASCA conduct a study of the needs of Canadian astronomy in the area of space astrophysics to inform the next Long Range Plan.

The MTRC commends the CSA for hiring astronomers whose responsibilities will include an active research program at the CSA. **The MTRC further recommends** that the ties between the CSA and the astronomical community be further strengthened by altering the membership of the JCSA to ensure broader representation by the astronomy community.

B. Second Generation (2010-2020)

Overview

The LRPP strongly recommended that Canada plan to participate in two major World Observatories of the Second Generation - the SKA and the VLOT, both slated for construction during 2010-2020. The scientific opportunities and technical challenges of these unique projects, together with Canada's reputation, provided a compelling case for the LRPP recommendation, and the MTRC finds these arguments to be equally compelling today. The SKA concept is that of a huge radio telescope array for centimetre wavelengths, whose collecting aperture is equivalent to one square kilometre. Its collecting area and sensitivity are nearly one hundred times larger than the largest radio telescope operating today. The aperture area of the currently proposed VLOT is about ten times larger than any existing telescope. The current status of these initiatives is discussed separately below.

In the LRP the timelines for these two projects were envisaged to be similar, but that is no longer the case. At present the SKA is not a full project, meaning that no formal participation agreements have been signed. The site and the array design have not yet been selected, although these decisions are expected to be made within the next few years. Canada is developing one array technology called the Large Adaptive Reflector or LAR, which is now well advanced. After the SKA consortium moves to the status of formal agreements and selects the site and telescope array technology, it is anticipated that one or more prototype demonstrator elements will be built leading to the start of construction. At present the Canadian LAR development project (referred to as the Phase B Study) is not fully funded. Current funding expires in 2004-05, and financial support for its completion by 2008 is thus now required. Meanwhile, Canada has grasped an opportunity to join the VLOT/TMT project. The current consortium is made up of Canada and three US partners. A detailed design study, the DDP, is underway and will be completed in 2008, with construction to begin at about that time. Canada's share of the DDP, building on existing VLOT design work, urgently requires financial support to permit Canada's continued partnership in the project.

Canada has a leading role in both the SKA and VLOT/TMT. The two projects are highly complementary and both are essential in answering fundamental scientific questions. Accordingly the timely completion of the relevant studies for both projects is vital.

(a) Square Kilometer Array (SKA)

The LRP contains the following recommendations concerning the SKA:

The LRPP strongly recommends that the Canadian LAR concept be carried forward into prototypes for key component (phase B) studies. This study should be one of the highest priorities among moderate size projects. A rigorous review of the results as well as the science goals and design status of the SKA project should then be carried out (in approximately five years' time).

The LRPP recommends that a development envelope be established that would fund the construction of a LAR prototype, if recommended by the Phase B review.

The LRPP recommends that Canada position itself now for entry into the construction of the SKA.

The SKA concept is that of a giant array of radio telescopes operating over a contiguous frequency range 0.15 - 22 GHz. As noted earlier, the total collecting aperture will be about one million square meters, nearly two orders of magnitude larger than that of the largest existing or any other planned radio telescope. The array of antennas will be configured to provide a maximum baseline of several thousand kilometres, affording an angular resolution at the highest frequency of better than one thousandth of an arc-second. The SKA science reach will be extraordinary, allowing new discoveries in the nature of Dark Energy, the structure of universe before "first light", the formation of the first stars, and new and sensitive tests of general relativity. Furthermore, its range in frequency and angular resolution, coupled with its very high sensitivity to weak cosmic radio signals, makes it highly complementary to the other powerful LRP facilities such as ALMA, JWST and TMT.

The development of the unique LAR concept for the design of the SKA is a prime example of an innovative idea involving a partnership among government, universities, and industry.

Canada is already a strong player in the development of the SKA concept. The founding chair of the international science steering committee was a Canadian, and many more Canadians are actively involved in the planning for this facility. There are now 15 countries involved, representing 34 institutes, and Canada is among the leaders of these. One reason for this substantial role by Canada is its strong scientific and technical leadership in centimetre radio astronomy, derived in part from the NRC-HIA's longstanding operation of the radio synthesis telescope at the DRAO. Another factor is Canada's achievement as the first country to successfully operate a Very Long Baseline Interferometer in 1967. This experience and leadership has placed Canada as one of the leading contenders to provide the technological solution to build the elements of the array.

Conventional methods of building collecting apertures are too expensive for such a large total area, and a number of designs are being developed around the world. Canada's solution is the LAR, proposed as a cost effective way to build large single radio telescopes as individual elements of the array. The concept involves a comparatively flat shapeable or adaptable reflector on the ground with an extremely long focal length. The focal plane of this reflector is located several hundred metres above the ground, where a focal plane array of antennas and receivers would be located to receive and process the signals. The focal plane array would be situated on a platform borne by a tethered aerostat. The recommendations made by the LRP strongly supported Canada's attempt to position itself as a leader in the SKA project using this design.

The LRP recommendations are being implemented, and considerable progress is being made in the design and development of the LAR concept, termed the Phase B Study. The design is regarded by the international SKA consortium as one of two which are nearly fully compliant with answering the scientific questions to be addressed by the SKA. Figure 4.3 shows the considerable progress made in the Phase B Study which includes the construction and operation of a prototype reflector segment, an aerostat, and winch system for aerostat control.

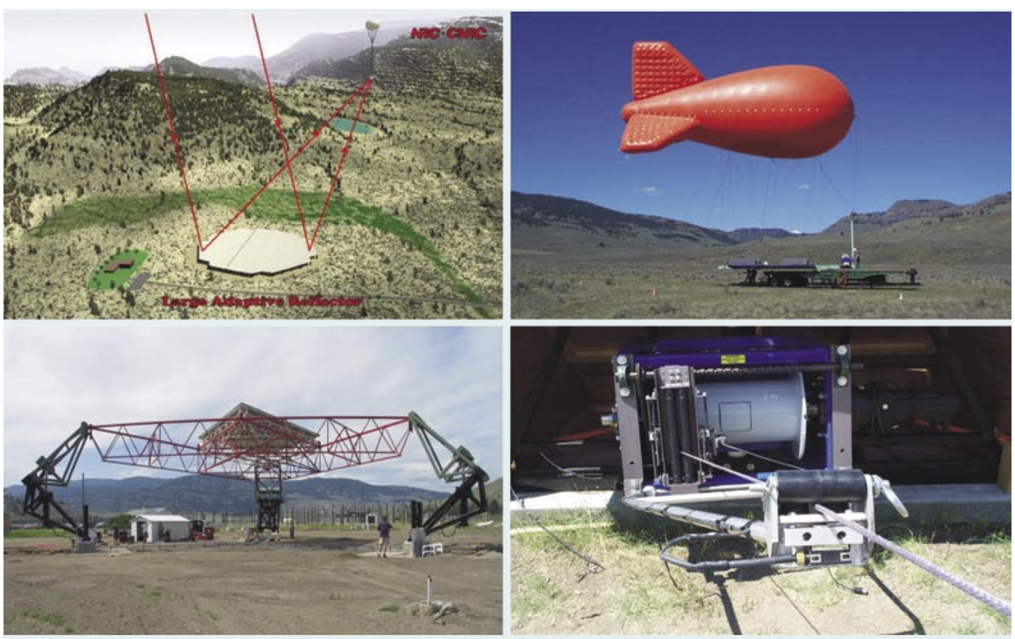

Figure 4.3: Upper left: conceptual image of LAR showing paths of radio waves as they arrive from a distant source, and are reflected and focused up to the aerostat-supported radio receiver. Upper right: prototype aerostat for supporting focal plane array being tested at DRAO. Lower left: prototype of section of reflector. Lower right: winch assembly for controlling position of aerostat.

Credit: NRC-HIA

The MTRC reaffirms the LRPP's strong support for Canadian participation in the SKA. Moreover, it strongly commends the Canadian SKA concept development team for its ingenuity in devising the LAR as one of the leading design options for the SKA. The committee recognizes, as did the LRPP, the tremendous potential for major Canadian leadership in developing the SKA should the Canadian LAR concept be chosen. However, Canada needs to join the SKA regardless of whether or not the LAR is selected, since the decision should be driven by the science and the relevance of Canadian technical prowess for the technology required. The MTRC recognizes the need to nurture the development of this technology, including the LAR concept, and strongly recommends that necessary resources be found to complete the Phase B Study.

An amount of approximately $9.5M is required for 2005-06 through 2008-09 for the remaining LAR development work in the Phase B Study. This work is at a critical juncture, and could suffer deleterious consequences if not supported adequately in a timely way. This project must be fully supported in order to permit its completion in time for the selection of the SKA design. According to the current schedule prepared by the International SKA Science Steering Committee, the selection of the design for the SKA elements will be made in 2008, and that construction will begin in 2012. It is also important for the momentum to continue beyond the end of the Phase B Study period, as the SKA becomes a fully defined project. If the SKA design is selected, Canada would probably be required to construct a full scale prototype LAR. If it is not selected, then Canada should participate in developing alternative SKA prototype components based on other products of the Phase B Study or on other areas of its expertise in radio astronomy instrumentation. Possible areas include focal-plane array feeds, beam forming technology, and ultra-high bandwidth data transmission, correlators, and data processing technology. The MTRC recommends an allowance of C$15M be made for prototype development beyond the time when the technology for the SKA is selected.

The LAR project is a prime example of the development of an innovative idea involving a partnership among government, universities and industry. NRC-HIA is responsible for the concept, the electronics and testing. A university (McGill) is responsible for the aerostat technology, and industry (AMEC Dynamic Structures Ltd.) is developing the reflector and actuator design.

In summary, the MTRC makes the following recommendations concerning the SKA and LAR:

The MTRC strongly reaffirms the original LRPP recommendation that Canada position itself to play a leadership role in the international SKA initiative.

The MTRC strongly recommends that the Phase B Study, leading to a design of the Large Adaptive Reflector, be supported to ensure its successful and timely completion for the selection of the design of the SKA by the international SKA consortium. The Phase B Study should be at the highest priority level among moderate size projects.

The MTRC recommends that NRC-HIA plan to participate in the construction of prototype components of the SKA once the decision on the SKA technology has been made. This could be either an antenna element based on the LAR design, if this design is adopted by the SKA project, or other components based either on the work of the Phase B Study or on other expertise in radio astronomy instrumentation.

(b) Very Large Optical Telescope (VLOT)

The following recommendations concerning VLOT were made by the LRPP in January, 2001 as modifications to the recommendations in the original LRP document. This was done in the light of developments concerning the WF8m and advancing work around the world on VLOT designs:

The science case for the TMT, Canada's acknowledged expertise in VLOT design, and the strongly favourable review by the CFI together make a compelling case to move forward on this project with a high level of urgency.

The LRPP strongly recommends that funding to support a design team for a Very Large Optical Telescope (VLOT) be made available as soon as possible. This team will enable Canada to play a critical role in the design and construction of a VLOT whose diameter is envisaged to lie in the 20-30 metre range. This telescope would be designed, built, and operated in cooperation with international partners. This should be one of the highest priorities among the moderate sized projects. The design team should also have the extended mandate to simultaneously design a future Extremely Large Optical Telescope (ELOT) that is far larger than the VLOT. The ELOT would appear at some time later in the century. This is critical if Canada is to continue to play a role in the long term development of world observatories, as is clearly documented in the LRP.

The LRPP recommends that the WF8m project, discussed in the LRP, be dropped in favour of a larger diameter VLOT. The funding that was proposed for the WF8m project in the LRP, including funds for its design, construction, and operation, should be combined into the construction of a VLOT in the 20-30 metre range.

The LRP recommends that up to half of the Prototype Development Envelope proposed in the LRP be committed towards the design and construction of the VLOT. These funds should be released on the completion of a successful mid-course review.

In accordance with the LRP recommendation, NRC-HIA led a very successful design study of the VLOT. The VLOT Project Book, outlining the Canadian view of a design for a twenty metre telescope was completed in October, 2003, and 400 hardcopies were distributed. The subsequent development of the VLOT initiative has progressed much more rapidly than anticipated, and the LRP recommendations on the VLOT have been met and exceeded. Canada has become engaged with the TMT project. Figure 4.4 shows one concept of the TMT based on VLOT design studies undertaken in Canada.

Canadian involvement in the TMT partnership is being secured by ACURA in collaboration with NRC-HIA, currently forming an equal partnership with

Caltech, UC, and AURA. In this arrangement, the Canadian share of the project is 25 percent. This may be compared with our shares in the two other international optical facilities - Gemini at 15 percent (of both telescopes) and the Canada-France-Hawaii Telescope at 42.5 percent. The MTRC argues that, regardless of the exact percentage in the final share, a partnership equivalent to other major partners is important to ensure that Canadian astronomers will have access to telescope time sufficient to maximize the return to Canada of the scientific and technical benefits, and to ensure an appropriate measure of influence in project management.

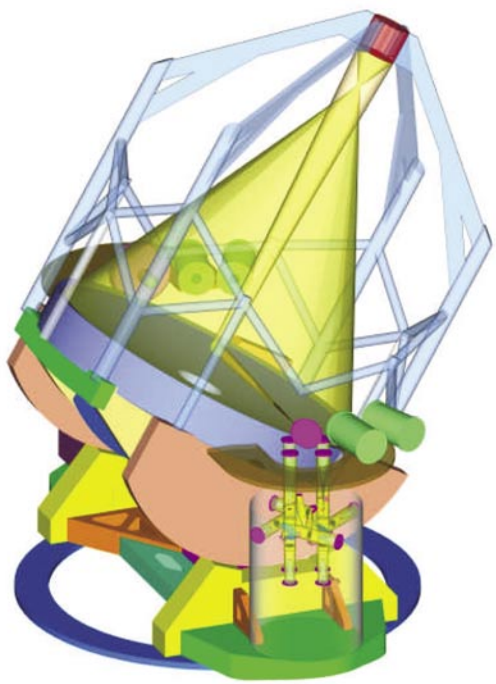

Figure 4.4: One possible concept of the TMT based on CAD modeling by Andre Anthony, NRC-HIA. The primary mirror shown at bottom of the telescope tube is thirty meters in diameter. For comparison, the height of a person would be represented by half the diameter of the hole shown at the centre of the primary mirror.

Credit: NRC-HIA

The science goals of the TMT include the imaging of extra-solar planets, the discovery of the "first light objects" (i.e. the first massive stars) in the universe, understanding star and planet and galaxy formation, and understanding the nature of cosmological Dark Matter and Dark Energy. As noted in Chapter 3, the TMT is strongly complementary to the JWST, ALMA and the SKA. The TMT will be the premier optical/infrared ground-based telescope in the world when it achieves its full operation phase expected some time in 2015.

The TMT is truly a large international project which, at this point in time, represents the very first VLOT design and one that has a good chance of being the first in operation. A total of 60 people across the total partnership are involved in the first major phase of development of the telescope - the DDP, which is scheduled to last four years. The international project office is located in Pasadena and it will be fully staffed in the late fall of 2004. The cost of this phase of the project is set at US$70M shared equally among the four partners. A total of US$35M has been granted by the Moore Foundation to support the Caltech-UC portion, and AURA has a large proposal before the NSF to fund its share of the DDP. Within Canada, the plan envisions that several sites will be involved with the DDP, including UBC (structural engineering, instrumentation, with AMEC Dynamic Structures Ltd. in Port Coquitlam, B.C.), NRC-HIA (adaptive optics, with the University of Victoria, observatory software, integrated modeling and site testing, with CFHT and UBC, computational fluid dynamics, with NRC's Institute for Aerospace Research), the University of Montreal (adaptive optics and instrumentation) and the University of Toronto (administrative headquarters, Canadian science center and computational fluid dynamics). As is the case for the LAR project, Canada's role in the VLOT/TMT is a prime example of innovation involving a partnership among government, universities and industry.

The application to CFI for a 25 percent partnership in the project received a highly favourable assessment and was accepted as a project outline pending the full development of a comprehensive project plan, including the operational phase. Up to a total of C$50M could be available from CFI for this project if it is approved, requiring a 60 percent matching component bringing the total to C$125M. This is half the total budget of C$250M needed for Canada's share before full operation begins in 2015.

To date, LRP funds expended on the VLOT project are as follows: 2001-02 $0.18M, 2002-04 $1.5M per year, 2004-05 $1.56M. The Canadian share of the DDP is C$25M , covering the period between 2004 and 2008. The current allocation of LRP funds ends on 31 March, 2005, so that the C$25M needed for Canada's share of the DDP will soon have to be found. CFI has approved a $10M request for interim funding by ACURA, subject to the condition that $6M of this amount in matching funds be identified, to maintain our present position within the DDP.

The TMT project plan calls for a conceptual design review in April, 2006, a September, 2008 start on construction, first light for some segments in 2014 and full science operations in January, 2015. Operating funds will be needed at this stage. The Canadian share of the operating support is estimated to be about C$25M annually. By contrast the current Canadian payments for all operations in astronomy are about $11M, rising to about $15M by 2010 as operating funds are required for ALMA. Although the operational support of some existing facilities may well be trimmed or stopped, it is quite clear that new operating support will have to be found to make the TMT possible for Canada.

The MTRC strongly advocates that the TMT project represents Canada's most effective way to take an international lead - together with its partners - in

VLOT scientific programs. Canada is poised to play a large role in this project, both scientifically and technically. For example, given our projected level of investment, it is recognized that Canada will supply at least one major structural component, the enclosure, and one leading scientific instrument, as well as contribute throughout the project. The reference design is now chosen, and the selection was based in part on studies conducted by a Canadian engineering team at NRC-HIA and AMEC Dynamic Structures Ltd. This is an outstanding example of the confidence placed in the Canadian team and a direct consequence of its VLOT studies to date.

To recapitulate, the capital funds required for this project are C$25M for the DDP and about C$225M for construction. The CFI has awarded $4M, subject to matching contribution of an additional $6M, to cover the first 2 years of the DDP, but an additional C$15M is needed shortly to cover the rest until 2008. The science case and the strongly favourable indications from the CFI make a compelling case to move forward with the TMT with a high level of urgency. Accordingly, the MTRC makes the following recommendations:

The MTRC strongly reaffirms the original LRPP recommendation that Canada position itself to play a leadership role in an international VLOT project. **The MTRC strongly endorses** the TMT project as Canada's route to achieve this goal.

The MTRC strongly recommends that the Detailed Design Phase of the TMT project be supported to fulfill Canada's obligation as an equal partner. This should be at the highest priority level among moderate size projects. CFI has made an interim award, contingent on securing matching funds. It is anticipated that both the Ontario and BC governments will soon contribute matching amounts, and HIA-NRC should participate by contributing matching funds as required to ensure that this major effort proceeds as planned.

The MTRC strongly recommends that a partnership for Canada in the TMT project, equivalent to that of the other major partners, be adopted as the current highest priority for funding of the construction of a new World Observatory facility.

4.4 National and International Observatories

International Observatories are defined here, as in the LRP, to involve limited international partnerships among a small number of partners. They are generally not unique in terms of overall scope as in the case of the World Observatories, but each is distinguished by unique features. Canada is currently involved in several space-based observatories, including Herschel/Planck, three ground-based international facilities, namely Gemini, CFHT and JCMT, and two ground-based national telescopes, namely the DRAO and the DAO.

A. Space-Based Observatories

A significant fraction of astrophysical research must unavoidably be conducted using space-based facilities because the needed data cannot be obtained from ground-based telescopes. Space-based astronomy has already added to our knowledge base and set new challenges that could not have been anticipated from ground-based data. For Canadian astrophysicists to be competitive with their peers in other countries, they must have access to such facilities, as well as have the capacity to participate in and to lead space-based missions in accordance with their astrophysical priorities. Moreover, space-based telescopes and their observations, when well communicated, have broad public appeal and are excellent vehicles for youth to consider careers in science and engineering and to respond to the public's strong interest in astronomy.

The MRTC strongly reaffirms the LRP recommendation for Canadian participation in Herschel/Planck and other space missions of high promise.

The creation of the CSA in 1989 has provided Canadian astronomers with a wide range of new opportunities in wavelengths from the ultraviolet to radio. Currently, Canada is involved in a number of space astronomy projects, including the JWST discussed earlier, and our participation in all of these is being conducted through the CSA. At the time of the LRP process, which concluded five years ago, the CSA was less than ten years old, but Canadian astronomers were already fully engaged through the FUSE, VSOP and BAM missions. Only five years later MOST and BLAST are underway and Canadian astronomers are anticipating the future Herschel/Planck and JWST telescopes.

The following recommendations were made by the LRPP concerning Hershel/Planck, formerly known as FIRST/Planck, and space-based VLBI:

The LRPP recommends that Canada, through the CSA, join and participate in the FIRST/Planck mission.

The LRPP recommends that an ongoing presence in space-based VLBI be maintained. Canada, through the CSA, should continue its contributions to this field.

The MTRC is pleased to note the strong participation by Canada in Herschel/Planck, as recommended in the LRP, and extends its appreciation to the CSA on behalf of the astronomy community for making this possible.

The MTRC is pleased to report that Canada, through the CSA, is participating in an increasing number of other astronomical space observatories, except for VSOP, from which Canada has withdrawn. Currently Canada's involvement includes:

- MOST: an all Canadian mini-satellite containing a very small payload designed to detect and study stellar oscillations; launched in 2003 and fully operational;
- FUSE: a NASA-led mission with significant Canadian involvement, designed ultraviolet spectroscopy on hot gas in galaxy haloes, including galaxy clusters, the Milky Way halo, the interstellar medium, and disks and debris around young stars; launched in 1999 and fully operational well beyond its nominal three-year lifetime;

• ODIN: a Swedish led mission with significant Canadian involvement, designed to study the chemistry and physics of interstellar gas, atmospheres of giant planets, and star formation in nearby galaxies; launched in 2001 and fully operational;

• BLAST: a multinational project which includes researchers from Canada, to probe the sub-mm sky with unprecedented sensitivity using balloon borne equipment, and will conduct unique galactic and extra-galactic surveys; successful test flight in 2003.

Figure 4.5 shows MOST prior to its launch on 30 June, 2003. This small satellite has yielded already a wealth of information on the subtle fluctuations in light whose study reveals a star's minute oscillations. These oscillations in turn reflect the structure interior to the star in a manner analogous to the way earthquakes reveal the interior structure of the Earth. The MTRC commends the CSA for its support of this mission. Moreover, the MTRC endorses the continued support for all the above-mentioned space-based missions, in order to ensure that our

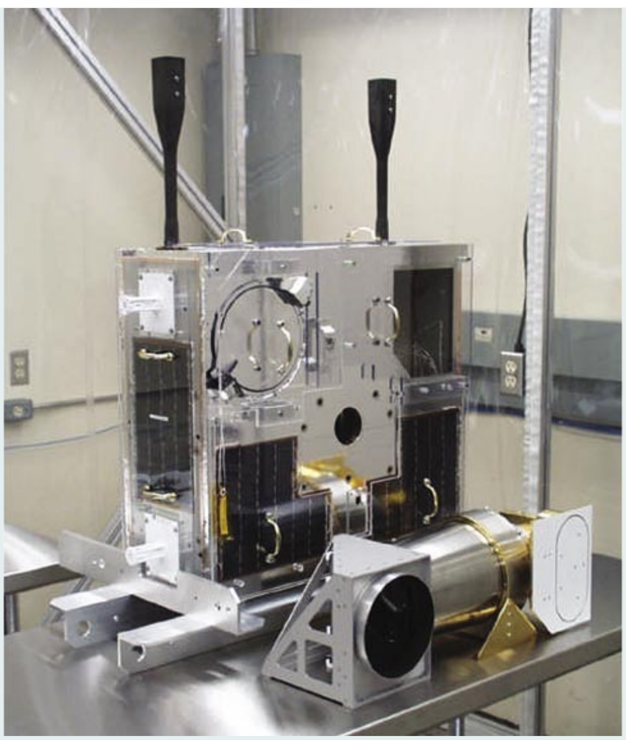

Figure 4.5: View of MOST before its launch in 2003. This small telescope was built using innovative technology developed at Dynacon, Inc. (Ontario), the University of Toronto Institute for Aerospace Studies, and the Department of Physics and Astronomy, University of British Columbia, and with the financial support of the Canadian Space Agency.

Credit: CSA and MOST satellite team

investment reaps the deserved scientific benefits while providing excellent training opportunities for future Canadian scientists and instrumentation engineers.

Finally, the MTRC notes that since the LRP was released, there is growing Canadian interest and expertise in High Energy Astrophysics. There have been at least nine faculty hires within the past four years in Canada with interests in this area. In addition, three of the fourteen Canada Research Chairs awarded in astronomy are in this field. These developments have the potential to increase the number of scientists involved in space astronomy and to lead the way to a new area of exciting space astronomy in Canada.

The MTRC makes the following affirmation and commendation:

The MTRC strongly reaffirms the LRPP's recommendation for Canadian participation in Herschel/Planck, and **commends** the CSA for its continuing commitment to Canada's participation in this and other space astronomy missions of high promise.

B. Ground-Based International Observatories

(a) Gemini

The LRP contains the following recommendation concerning ground-based international recommendation:

The LRPP strongly reaffirms Canada's commitment to the Gemini project over the coming decade. Gemini should be given the highest priority for the ongoing operation and support of our international observatories.

A second recommendation in the original LRP document, concerning the proposed WF8m, is not restated above because it was made obsolete by the January 2001 addendum to the LRP, recommending this initiative be discontinued in favour of the VLOT.

The Gemini project was initiated in the late 1980s. It is an international organization that built and manages twin eight metre telescopes - one in Hawaii called Gemini North, and the other in Chile called Gemini South. With a telescope in each hemisphere, Gemini is unique among 8-10 metre telescopes in offering full sky coverage to its partner communities. The partnership comprises the US (50.1%), Great Britain (23.8%), Canada (15.0%), Australia (6.2%), Argentina (2.4%), and Brazil (2.5%). Chile was originally a contributing partner at the five percent level, but in 2000 Chile withdrew as a regular partner and, with the agreement of the partnership, placed its capital contributions into a trust fund to support the development of Chilean astronomy. It maintained its ten percent share in Gemini South, as the host country, but freed up its five percent partner share. This share was absorbed by the consortium. Canada used LRP and WESTAR Corporation funds to purchase its proportionate share of Chile's time on the telescopes. The cost of the construction buyout was about

US$1.4M (LRP $1M, WESTAR $0.4M). The increase in operating funds amounted to US$190K per year, and this amount also came from LRP funds allocated to NRC-HIA. In addition, NRC has contributed a small sum in exchange for increased time, on a one-time basis, to assist the partnership in meeting the overall financial needs of the observatory.

During the last several years Gemini has ramped up to about 75 percent science time across both telescopes, which is the sustainable level for full science operations. The remaining 25 percent is devoted to instrument commissioning, maintenance and development. Gemini highlights from the Canadian perspective during the first five years of the LRP include the delivery of the Data Handling System and Gemini Science Archive (provided by the CADC), GMOS imager/spectrographs for both telescopes, the successful commissioning of the adaptive optics system ALTAIR, and Vancouver's hosting of the first ever Gemini Science Meeting (May, 2004). The MTRC notes that the instruments supplied by Canada to Gemini have all been uniformly successful. They arrived on time, were put into successful operation almost immediately, and constitute the "real workhorse" instruments of the telescope. NRC-HIA is to be commended for its achievements in this area. One of these accomplishments is highlighted in Figure 4.6, which shows the remarkable improvement in resolution with Gemini when using ALTAIR to correct for the effects of turbulence in the atmosphere.

The instruments supplied by Canada to Gemini have all been uniformly successful and constitute the "real workhorse" instruments of the telescope, strengthening the argument for a major contribution by Canada to the new program for developing and building the next generation instruments for Gemini.

The total contributions to Gemini operations from LRP funds has amounted to approximately US$2.4M, US$2.5M and US$1.5M in 2002, 2003 and 2004 respectively. These were used to partially offset the growth in operating costs. While the LRP support has provided some relief for the shortfall, the MTRC recommends that a permanent solution be found for the ongoing support needed.

Both Gemini telescopes are queue-scheduled, meaning that the programs carried out on a particular night are the ones appropriate to the observing conditions. The Gemini queue is ordered so that the highest ranked proposals from the peer review process have preferred access to the observing conditions best suited for those programs. The queue is executed in service mode by trained Gemini staff, and therefore the astronomer whose program is being carried out is generally not physically present at the telescope. Queue-based observing provides for more efficient use of the telescopes, especially considering the complexity of its instrumentation, and it also saves travel funds for investigators and helps university faculty users to maintain their normal teaching schedules. It also forces observers to develop careful, clear instructions for assessing when data of adequate quality have been obtained, thus also minimizing judgment errors at high altitude by tired visiting astronomers. In the original management plan for Gemini it was envisioned that there would be a 50-50 split between normal (observer assigned particular nights) and queue-scheduled observations. With a 75 percent queue, Gemini is in need of increased operating funds if queue operations are to remain at that high level. Gemini is seeking additional funds for operations and maintenance for this purpose, beginning in 2006, with the consequence that the Canadian share could increase by approximately C$1.25M per year by 2008.

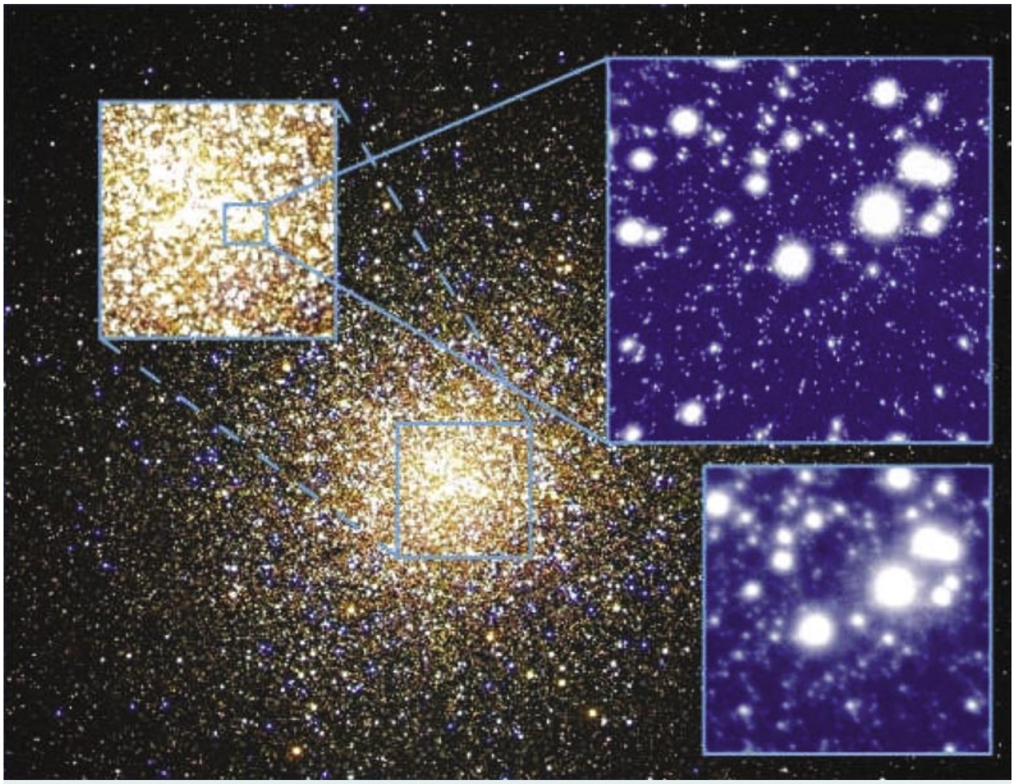

Figure 4.6: The ancient star cluster M13 imaged using the adaptive optics camera ALTAIR on Gemini North. The central region imaged is very crowded. The blue inset at the top shows the image obtained with ALTAIR. It has an angular resolution of 0.06 arc-sec, whereas the lower blue inset shows the image without ALTAIR at a resolution of 0.26 arc-sec. The angular resolution with ALTAIR is comparable to that achievable with the Hubble Space Telescope. Such images will allow astronomers to find the lowest mass stars that can burn hydrogen in the cluster, and to make important new discoveries on the content, age and evolution of these systems.

Credit: Gemini Observatory; wide-field background image courtesy of the Canada-France-Hawaii Telescope/Coelum

significant need for Gemini now is new instrumentation. In 2001 the Gemini Board initiated a process, termed the "Aspen process", to define Gemini's science and instrumentation goals for the next decade. This was a science driven process and involved wide community involvement and consultation. A number of meetings were first held in various partner countries to consider their priorities. In Canada, this meeting was held in Montreal in May, 2003 with about 25 participants. The Montreal meeting was designed to ensure that Canadian interests and positions would be well formulated for a subsequent international meeting at Aspen, Colorado in June, 2003. Attendance at Aspen was restricted to about 90 astronomers from the entire Gemini community to permit a workshop format, and the outcome led to the choice of an exciting complement of instruments:

• **Extreme Adaptive Optics Coronograph** to image, for the first time, planets outside our own Solar System. Canada is part of an international team investigating the design for this instrument;

• **High Resolution Near Infrared Spectrograph** to explore the chemical composition of the gas clouds in our Galaxy out of which new stars, planets and possibly other life, form.

In addition there are feasibility studies for two further instruments:

• **Wide Field Multi-Object Optical Spectrometer** to investigate and characterize the Dark Energy which dominates the mass-energy of the universe, and about which very little is currently known (see also Chapter 3);

• **Ground Layer Adaptive Optics System** which has the potential to observe the first stars ever formed in the universe. Canada is involved in a feasibility study for this latter instrument.

These design/feasibility studies are being funded through currently available instrumentation funds at Gemini, but the estimated total cost for the proposed instruments is approximately US$70M. For Canada to finance its share of the cost of the next generation Gemini instrumentation will require about C$15M over the period 2006-11.

The MTRC considers the "Aspen Process" instruments an essential enhancement for Gemini. The instruments are necessary to permit Gemini to participate in the science described above and in Chapter 3, and the emphasis on a powerful adaptive optics capability will enable astronomers to realize the full potential of the telescope aperture in achieving high sensitivity and resolution. It is not just telescope aperture that counts, but also how effectively the light is used. These instruments were not envisaged in the LRP, but their consideration at this time is driven by scientific need and the developments in worldwide technology in astronomical instrumentation.

This program offers an opportunity for the university community to play an important role in developing astronomical instrumentation. The realization of this opportunity requires university groups to use funding mechanisms available through NSERC and CFI to build the necessary capabilities within the university sector, and to contribute directly to the cost and construction of the instruments.

In view of these considerations, the MTRC makes the following recommendations:

The MTRC reaffirms the LRPP recommendation that Gemini should be given highest priority for ongoing operations support among our international projects. **The MTRC recommends** that Canada support the plan for Gemini to operate in a mode in which most programs are conducted under queue and service observing.

The MTRC strongly endorses the participation of Canada in providing its share of the new instrumentation required to address the forefront scientific questions of broad interest.

(b) The Canada-France-Hawaii Telescope (CFHT)

The LRPP made the following recommendation concerning the CFHT:

The LRPP recommends that the MegaPrime camera, as well as the wide-field infrared camera, WIRcam, be funded at CFHT.

Canada has a 42.5 percent share in the CFHT. Among telescopes in its class, the CFHT has enjoyed a reputation for the sharpest images of any ground-based telescope in the world. According to a study of citations published in 2001 by C.R. Benn and S.F. Sanchez (Publications of the Astronomical Society of the Pacific, vol. 113, pp 385-396, 2001), the CFHT was by a significant margin the most productive telescope in its class during the 1991-98 period of the study. The CFHT is now outfitted with MegaCam, a powerful wide-field camera in the optical, and will soon be outfitted with WIRCam, a powerful wide field infrared camera. These two instruments, advocated in the LRP, will greatly enhance the telescope's scientific capabilities. MegaCam is the world's largest imaging camera with over 300 million picture elements. It became operational in 2003, providing the unique capability to observe a full one square degree of the sky (equivalent to the area of four full moons) with a single exposure. Large teams of astronomers from Canada and France are now carrying out major research studies such as the CFHT Legacy Survey (CFHTLS), which has been allocated about half of the dark and gray observing time with MegaCam over five years. This survey is providing a substantial archive that Canadian astronomers are using for a variety of research programs ranging from characterizing the expansion of the universe to finding the most primitive members of our Solar System. The WIRCam project involves collaboration with observatories in Korea and Taiwan, who provided financial resources for this project in exchange for receiving observing time on CFHT. This arrangement permitted NRC-HIA to direct LRP funds from CFHT to Gemini operations where they were urgently needed.

The CFHT has also been one of the world leaders in adaptive optics technology. Much of the Canadian effort in adaptive optics is now necessarily concentrated on Gemini, though the CFHT staff is continuing to improve the adaptive optics systems as resources permit.

Financial support for operating the CFHT is a major issue. Operating costs were frozen in 1995 and, at the current level of operation, the CFHT will suffer an operating deficit in 2004 and beyond. Canada has a substantial investment in this telescope and great care must be taken to continue to maximize the benefits of this investment. MegaCam has been an exciting and productive development, and with the equally exciting WIRCam nearing completion, the goals for the CFHT expressed in the LRP will soon be realized. The CFHT should continue to be exploited until the science is no longer compelling. Beyond this time, the operating funds should be re-directed toward higher priority facilities as needed. Accordingly, the MTRC offers the following recommendation:

The MTRC recommends that Canada continue to participate in CFHT for as long as the science produced by its new instruments remains compelling. A redirection of CFHT support to higher priority facilities should be considered, as needed, toward the end of this decade.

(c) The James Clerk Maxwell Telescope (JCMT)

The LRPP made the following recommendations concerning the JCMT:

The LRPP recommends that as our various scientific and technical commitments to the JCMT are completed, priority for resources invested in the JCMT be given to the support of the ALMA project as needed.

The JCMT is the leading sub-mm telescope in the world. Canada has a 25 percent share of the observing time on this telescope. As is the case for the CFHT, the citation study referred to in section 4.4B(b) shows that the JCMT was the most productive telescope in its class during the 1991-98 period of the study. The LRP recommendation above was made in the anticipation that Canada's commitments to the JCMT would be complete toward the end of the decade. The MTRC regards the strategy in this LRP recommendation to be still appropriate, as ALMA is now underway and will soon need operating support, and the tripartite agreement on JCMT comes to an end in May, 2009. However, the MTRC also notes that JCMT will soon acquire new and powerful instruments, which will keep the JCMT at the leading edge of sub-mm astronomy. HARP-B, a 16-element heterodyne focal plane array, which is a wide-field camera for spectroscopy of the atoms and molecules in the warm interstellar gas, will arrive in 2005. SCUBA-2, the most powerful wide-field submillimetre camera in the world for mapping cosmic dust emission, will arrive in 2006. SCUBA-2 is designed to be a thousand times more powerful than its predecessor SCUBA, also on the JCMT. The latter instrument is already a key element of the success of the JCMT as the world's most powerful sub-mm telescope. Its scientific importance and the support provided by JCMT staff are together responsible for creating a demand for the JCMT, not only by radio astronomers but other astronomers as well, across the entire world.

SCUBA-2 represents the most exciting development in ground-based sub-mm astronomy at the current time. It will be used to investigate the evolution of galaxies at the epoch of galaxy formation by taking advantage of the high luminosity of these galaxies in the far-infrared coupled with the large redshift of these distant galaxies produced by the expansion of the universe. It is being developed by an international consortium, with significant participation by Canadian universities through a grant from CFI. SCUBA-2 became a prospect for Canada too late for inclusion in the LRP, but the imminent completion of SCUBA-2 needs to be recognized and taken into account, especially since

SCUBA-2 surveys are also likely to further transform our knowledge of the early universe. Also, HARP-B provides an unprecedented opportunity to map large regions of the Milky Way and beyond in the sub-mm part of the spectrum emitted by molecules in regions of comparatively high density and temperature. As such it is a powerful probe of the warmer and denser regions of the molecular universe.

These new developments provide a strong argument for keeping the JCMT in operation somewhat longer than originally envisaged to permit the full scientific benefits of these new instruments to be realized. Consequently, a final decision to withdraw from the JCMT should not be taken without a full assessment of the scientific value of these instruments, especially SCUBA-2. Accordingly, the MTRC offers the following recommendation:

The MTRC reaffirms the LRPP recommendation to phase out Canada's involvement with the JCMT as our various scientific and technical commitments are completed, and to transfer the operating support to ALMA. **The MTRC also recommends** that a final decision on when to end Canada's commitment should not be taken without a full assessment of the scientific value of SCUBA-2 on JCMT and the possible benefits of extending the term of Canada's involvement in this telescope by a few years.

C. Ground-Based National Observatories

(a) Dominion Radio Astrophysical Observatory (DRAO)

The following recommendation was made by the LRPP concerning DRAO:

The LRPP recommends that the planned Extended Canadian Galactic Plane Survey at DRAO be carried out until 2005.

NRC-HIA's DRAO is responsible for a highly successful program of radio astronomy, including the Canadian Galactic Plane Survey (CGPS), development of the WIDAR correlator for the EVLA, and the development of the LAR for the SKA. It has also been highly productive in training engineering and science students in cooperation with neighbouring universities. The DRAO received some LRP funds to assist in maintaining the calibre of the radio astronomy group, especially in the area of correlator design. The MTRC believes this support should continue, as recommended in section 4.3A(a).

The CGPS has been a highly successful project that has had significant impact on our understanding of the galactic interstellar medium. It has served as an exemplary model for other countries and indeed has evolved into a worldwide collaboration, known as the International Galactic Plane Survey (IGPS). Moreover, it has fostered extensive collaborative links between the NRC and universities, as well as the training of the next generation of Canadian radio astronomers. The LRPP recommended that the CGPS be carried out at DRAO until 2005. The existing LRP allocation for the CGPS is adequate to complete the section of the project originally envisioned in the LRP, so no new additional funds are requested or required for this component. However, the CGPS team intends to complete the survey of the remaining section of the galactic plane visible from DRAO and merging of the three international interferometric surveys (and the FCRAO CO surveys) into a single scientific database and image of the Milky Way. This is part of a collaborative project with scientists who will be using the Herschel telescope. This extended IGPS project should take until 2007. The committee endorses the extension of this project until 2007, and recommends that LRP support be continued until this phase is complete.

The MTRC recommends that the previously allocated NRC LRP funding for the Canadian Galactic Plane Survey be continued at the current rate until 2007 to enable a proposed extension within the International Galactic Plane Survey program.

(b) Dominion Astrophysical Observatory (DAO)

The LRPP made the following recommendation concerning the DAO telescopes:

The LRPP recommends that the two DAO 1.8 and 1.2 metre telescopes be supported over the coming decade. These facilities should be provided with the extra staff and support needed to maintain their scientific productivity.

LRP funding for the DAO telescopes, though modest, has been very important. Canadians receive large allocations of time on these telescopes for long term monitoring, thesis projects or as test beds for new instrumentation. The Plaskett 1.8 metre Telescope also plays an important role in public outreach. The LRP recommendation for funding was $100K per year, whereas in fact $50K per year has been allocated. Of this amount $25K per year was used to hire two engineering co-op students, a short-term machinist and an IRAF programmer. About $15K per year was directed towards augmenting operations. A closed cycle cooler for the instruments has improved operational safety and efficiency, while the Herzberg spectrograph, recently returned from CFHT, is being fibre-optically coupled to the Plaskett Telescope for rapid switching between imaging and spectroscopy. The 1.2 metre telescope is also productive, for example operating on a 30 night run supporting MOST observations. This telescope has also benefited from some upgrades as a result of the modest LRP funding.

Both telescopes are still scientifically productive, and they do deserve modest LRP support. The MTRC recommends that both telescopes receive this support.

The MTRC recommends that the current LRP support for the enhancement of the scientific capabilities of the DAO telescopes be continued.

4.5 People

The LRP contains the following recommendations concerning people:

The LRPP strongly recommends that at least six additional staff astronomers, of the highest calibre, be hired for the HIA. This must be one of the highest priorities in funding new people. There must be a concerted effort to rebuild the HIA staff both to fuel Canada's participation in the coming world observatories and to maintain our present international commitments. The HIA should also play an increased role in front-rank research and leadership.

The LRPP recommends that CITA be supported with the financial, human, and computational resources required to enhance its position as one of the world's pre-eminent centres for astrophysical research.

The LRPP strongly recommends that university laboratories for experimental astrophysics be created. This should be one of the highest priorities for modest size projects in the coming decade. They could be supported by NSERC, as well as other agencies, and by commitments of infrastructure and faculty positions from the host universities.

The LRPP strongly recommends that postdoctoral fellowships of the highest international stature and levels of competitive funding, comparable to Hubble Fellowships, be established. This should be among the highest priorities in funding new people. Two new Fellowship programs should be established:

1. NSERC and CSA should jointly initiate a new fellowship program, featuring at least six, 3 year postdoctoral fellows, awarded through the highest level international competition and funding, open to Canadians and non-Canadians alike, and to be tenable at any Canadian university or CITA.

2. Similarly, NRC should initiate a similarly new Herzberg Fellowship program consisting of a total of six, 3 year Herzberg postdoctoral fellows, tenable at any NRC astronomy facility or laboratory.

The LRPP recommends that NSERC continue its commitment to the proven, outstanding postdoctoral program at CITA. NSERC should also further increase the total funding to the individual operating grants program. It should use these extra funds to enable individual excellent Canadian researchers to support a post-doc within their group.

The MTRC notes that, although there is some progress, most of the above recommendations on people, though exceptionally vital, are not yet implemented.

Several young scientific staff members of excellent calibre have been hired at NRC-HIA, partly through LRP funding and partly through NRC's newly established New Horizons/New Opportunities Program. Rather than providing new base funding (as envisioned by the LRP), the latter program provides three year term bridges to future retirements.

Concerning the second recommendation on CITA resources, there have been several welcome developments since the LRP was released. NSERC funding for the institute and its national programs was increased substantially in the competitive reallocation exercise. The University of Toronto, the host institution, has hired two additional professors in CITA. The Cosmology and Gravity program of the Canadian Institute for Advanced Research , in which CITA participates strongly, has been renewed. High performance computational resources have been put in place through a CFI award. All of this support has enhanced CITA's position as one of the world's pre-eminent centres for astrophysical research.

Regarding the third recommendation on support for university labs in experimental astrophysics, the CSA and NRC-HIA are supporting an Industrial Research Chair at the University of Montreal, thereby strengthening Montreal's capability in ground-based and space-borne astronomical instrumentation. In addition, the University of Victoria has established an instrumentation laboratory in collaboration with NRC-HIA, and with the support of a CFI grant. These are important examples of the kinds of initiatives proposed by the LRP, but they are still comparatively rare.

The fourth recommendation has been partially implemented following the announcement by the CSA of a new program of postdoctoral fellowships beginning soon, each at the level of $60K per year. There will be a total of six fellowships for the space sciences. It is anticipated that one of these will be for space astronomy.

All of the above are commendable activities which move part way along the path to a successful implementation of this part of the LRP. The above successes notwithstanding, there is a long way to go in realizing the full scope of the LRP requirements. The MTRC reiterates the importance of new university instrument labs for space and ground-based astronomy and of providing increased grant support to university investigators to maximize the benefits of the LRP. The new staff positions at NRC-HIA are making critical contributions to the support of the international facilities such as Gemini, CFHT and JCMT, as well as to the CADC. It is important that these positions be sustained and that new staff be hired to reach and exceed the original levels recommended by the LRPP. The MTRC believes that the enhancement of the NRC-HIA and NSERC postdoctoral fellowship programs beyond current levels is a key element of the overall success of the LRP. Such programs, similar to the Hubble and Chandra Fellowships in the US, would be an important factor in enabling the most talented astronomers to hone their skills by using LRP facilities. An early start to these enhancements is important in the light of accelerated activity, particularly on the VLOT/TMT.

In keeping with the earlier timeline for TMT/VLOT and with the anticipated buildup of momentum on the SKA following the decision on the SKA technology, the MTRC strongly recommends that the levels of research personnel be increased from the six advocated in the LRP to ten, applicable to HIA-NRC research positions, Herzberg Fellowships, and the NSERC/CSA fellowships in astronomy. The increases at NRC-HIA would require corresponding increases in infrastructure to accommodate these staff, and these increases would have to be planned for soon. The level of ten in all areas described should be reached by the time of first light of the TMT to permit an early response to the new opportunities created by this facility.

While the increased staffing levels discussed above are directed principally toward NRC-HIA, there is a need for a commensurate increase in research faculty positions within the universities to fulfill the potential of the LRP, and the MTRC recommends with equal force that planning be undertaken now by the universities to make such increases possible. It is especially important to hire faculty skilled in the design and construction of space and ground-based telescope instrumentation to establish and/or enhance the recommended university laboratories for experimental astrophysics. The universities need to develop policies to ensure that faculty with these particular skills are well recognized and rewarded for the impact of the instruments they develop and build, and not just on their publication record. The publication record alone for instrument scientists is not the full measure of their academic research contributions.

It is the MTRC's view that the goals of the MTR recommendations relating to NSERC support for instrumentation labs and an enhanced fellowship program can be most effectively achieved by transforming the astronomy grants program to an envelope funding system. Such a system would provide the flexibility needed to award grants targeting these areas. Envelope funding has served the subatomic physics community well, and there are many similarities between this community and astronomy. ACURA is currently the organization best positioned to engage CASCA and NSERC in discussions leading to the implementation of such a system.

The MTRC makes the following recommendations:

Canada's role in the development of the SKA and the rapidly advancing TMT project argue for an increase in the complement of skilled researchers over that recommended in the LRP.

The MRTC commends the partial fulfillment of the LRP recommendations in the acquisition of new staff positions at NRC-HIA and the introduction of a new postdoctoral fellowship program in space science announced by the CSA. **The MRTC re-affirms and re-iterates** the LRP recommendations on the building of university labs in experimental astrophysics, increased grant support for university researchers in astronomy, and the importance of building strength in research positions in both the university and government sectors of astronomy to realize the full benefit of the LRP facilities. In view of the anticipated demands for research personnel to fill the needs of the SKA development and the TMT, **the MTRC strongly recommends** that the number of NRC-HIA research positions, Herzberg Fellowships, and NSERC/CSA fellowships all be increased to ten from the six recommended in the LRP. This level should be reached before first light on the TMT. There should be commensurate increases in the numbers of university researchers in astronomy, especially in the area of instrumentation in both space and ground-based astronomy.

The MRTC recommends that ACURA, representing all Canadian universities active in astronomy, consult with CASCA and NSERC with the view to transforming the astronomy grants program to an envelope funding system. Such a system would provide allocations to facilitate the establishment of new university laboratories in experimental astrophysics and the operation of the NSERC/CSA fellowship program described in the previous recommendation.

4.6 Computation

The LRP included the following recommendations concerning Canada's strategy for computing:

The LRPP strongly recommends that the CADC host archives of data from upcoming space and ground-based observatories, and develop innovative data mining techniques for their exploration. This should be one of the highest priorities among the computational projects.

The LRPP strongly recommends that funds be allocated toward the support and upgrade of a mid-range parallel computer plus a local user-support person. This should be one of the highest priorities among computational projects. Furthermore, this capability should be located at CITA to provide national high performance computing for modeling and simulations.

The LRPP recommends that the funding towards equipment grants in the country be substantially increased to enable researchers to keep pace with the huge volumes of data and computation that will shortly become standard in astronomy and astrophysics.

The LRPP recommends that a sustainable, nationally funded multidisciplinary HPC network be established through initiatives made possible by the CFI program.

The first recommendation, in many respects, stands apart from the final three. The activities of the CADC are highly focused and provided as a service by NRC-HIA. The remaining recommendations are focused on research in universities and are somewhat, but certainly not exclusively, focused on support of theory.

A. The Canadian Astronomy Data Centre (CADC) and Data Analysis

Since publication of the LRP, NRC-HIA's CADC has met the recommendations of the LRPP and is becoming one of the principal data archiving and data mining facilities worldwide. This activity is referred to as the Canadian Virtual Observatory (CVO), and is becoming the principal focus of the CADC. This role is part of an emerging and essential worldwide activity providing the tools to efficiently access and analyze archived data from all major telescopes. The focus of the CVO has been in two distinct areas: the CFHTLS, using MegaCam data, and the development of general data mining tools for astrophysics. In both areas, financial support has been allocated from LRP funds (at the recommended amount of $300K per annum) and capital support from NRC-HIA and the CSA. Financial contributions from the latter two sources amount to $2.4M to date since the release of the LRP. The CADC has also successfully initiated the Gemini Science Archive, which is now a key part of the CVO and thus of the

IVO, its international counterpart. This is the only telescope archive at CADC which is funded by the observing facility itself. The CADC's role as the primary archive for CFHT, JCMT and CGPS data has been funded internally by NRC-HIA, while it receives partial support from CSA for its role in HST and FUSE archiving.

The accomplishments of the CADC are impressive. Figures provided to the MTRC include, for 2003 alone, service to more than 2000 distinct users accessing the CADC major data archives and the Digital Sky Survey service. Moreover, the usage is accelerating, since a comparable number of users have been served in only the first eight months of 2004. The most significant factors in the increasing rate of service are the large data sets from the CFHT cameras CFH12K and MegaCam, with CFHTLS images composing most of the MegaCam data. There is also evidence that the data are leading to well cited publications by the community. Though these figures do not yield a complete picture of how the CADC is being used, they are indicative of the success anticipated in the LRP.

These successes are leading to an increasing need for computing and data storage capacity, data management specialists, and space and utility costs. These demands may be outstripping NRC's capacity to provide the necessary resources. A major driver is, and will continue to be, the explosive growth in astronomical data worldwide. For example, the CADC is preparing to manage Canadian access to all the data from LRP projects such as ALMA, TMT and JWST, in addition to its current role in managing data from the HST, CFHT, CGPS and JCMT (soon to be augmented with data from SCUBA-2). The flow and storage of data from the existing and planned observatories constitutes a world-wide data management challenge. Just as international consortia were created to build the world's most powerful telescopes, thereby offsetting prohibitive expenses for any one nation, a similar era may already be dawning for computation and data management.

The MTRC considers that a fundamental reassessment needs to be conducted at an international level to determine how to manage the worldwide data explosion associated with international observatory facilities. Meanwhile, the MTRC recommends that the NRC conduct a review of Canada's role in worldwide data management to guide its future development of the CADC.

The challenges faced by the CADC are closely coupled to the emerging problem of providing the tools to retrieve and analyze data acquired with LRP facilities, outlined in the third LRP recommendation above. This is a critical and urgent issue, and the agencies responsible for operating new LRP facilities need to have a plan to provide such tools. A lack of adequate data analysis capacity would place Canadian astronomers at a competitive disadvantage in publishing their work using LRP facilities, and so will adversely affect their capacity to use telescope time effectively. CASCA is well positioned to conduct an investigation of the needs of LRP facilities, and the MTRC recommends that such a study should be undertaken soon. This study should precede and contribute to the aforementioned review by NRC-HIA of the contributions of the CADC to Canada's role in global data management.

In summary, the MTRC offers the following recommendations:

The MTRC recommends that NRC-HIA conduct a review of Canada's role in global data management and the CADC's contributions to this role, particularly in light of the new ground-based and space-based facilities such as those described in the LRP. Meanwhile, LRP support for CADC should be continued to help maintain the strengths of the existing programs.

The MTRC recommends that CASCA, through its subcommittees, conduct a review of the data retrieval and analysis requirements of all LRP facilities, and then consult with NRC-HIA and ACURA to formulate a coherent strategy to address this issue. This should precede and provide input to the review by NRC-HIA of the contributions by the CADC to Canada's role in global data management contained in the previous recommendation.

B. High Performance Computing (HPC)

High performance computing (HPC) in astronomy is driven to a large extent by theoretical astrophysics, though certain kinds of intensive data processing requirements may also benefit from applying the most powerful computers available. The MTRC decided to focus on the application to theoretical studies since the need here is most urgent. The growing power of modern computers has spawned a new domain of research in astronomy - computational astrophysics. It provides the power to simulate the behaviour of cosmic structures for direct comparison with observation and, in many areas, it is the crucial link between theory, observation, and understanding. Canada has an excellent track record in HPC, with researchers making significant contributions in several areas including cosmology, magneto-hydrodynamics, planetary dynamics and numerical relativity. Canadian researchers have developed a disproportionate number of software packages and numerical methods used by practitioners worldwide.

As outlined on pages 81-82 of the LRP, it is convenient to classify computing levels in the form of a pyramid comprising three tiers. The base, Tier 3, represents the large number of desktops and small clusters. Tier 2 refers to the mid-level comprising systems which at present have up to several hundred processors. Tier 1, at the top of the pyramid, represents the small number of large, world-competitive systems comprising thousands of processors. All three levels play an important role in theoretical astrophysics and observational data analysis.

The first round of CFI funding for HPC in the summer of 1999 coincided approximately with the completion of the LRP report. Subsequent significant CFI funding of HPC installations have far exceeded that recommended in the last three of the LRP recommendations quoted at the beginning of section 4.6. Although the LRP recognized that CFI funding would have important implications for HPC in astronomy, it would have been hard to predict the total investment made in multidisciplinary HPC - to date over $240M including provincial matching funds. The $1.5M suggested in the LRP for Tier 2 computing was clearly very conservative. CFI investments have successfully established significant regional (mostly interdisciplinary) Tier 2 facilities and are generating a cadre of skilled computational scientists in many disciplines. The astronomy and general relativity communities have led in establishing and using many of these regional HPC consortia. However, HPC capability and the needs of computational astrophysics are evolving rapidly as the development of computing power makes possible increasingly sophisticated simulations of astrophysical phenomena.

The issue addressed specifically in this report is the lack of a Tier 1 system available to Canadian researchers in astrophysics, which is currently impeding, and will continue to impede, the interpretation of modern astronomical observations. Large scale HPC has been a central driver in studies of cosmic structure for over a decade and is becoming so in modeling of star and planet formation. Predicting gravitational radiation from coalescing black holes, understanding supernova core collapse and developing 3-D models of stellar structure also depend critically on large-scale computation. The current state-of-the-art in these areas on even the largest supercomputers is often many orders of magnitude short of that required to adequately represent such physical systems. The result is continual pressure to exploit the largest computers available in order to generate the most reliable models. The requirement is for a very specific type of computing, "capability computing", in which a single model spans several hundred or thousand tightly-coupled processors.

Tier 1 computing power is expected to grow by more than a factor 60 over the period 2005-11. In 2011, Tier 1 computing will permit remarkably realistic and detailed 3-D simulations of the interiors of stars and the rapid variations which occur when they explode to become supernovae. Comparisons will be made between the extensive observations of cosmic structure made with the most powerful telescopes discussed in this document with those predicted by simulations of the formation of this structure extending over the entirety of cosmic time. Figure 4.7 shows an example of a simulation (using a Tier 2 system) of the growth of cosmic structure as the universe expands over cosmic time. Even these crude simulations, together with observations, provide the seeds for understanding the still mysterious conditions which have shaped this structure. Both theoretical and observational astrophysicists using the sophisticated telescopes described in this document look forward with enthusiasm at the prospect of comparing observations with simulations to discover how the universe evolved to its present state.

An issue of concern in the strategy for Tier 1 HPC for astrophysics is the question of compatibility with the needs of other disciplines. The C3.ca organization, a collaboration of Canadian HPC interests, with the support of major funding agencies, is developing a strategy for long-term sustained support of multidisciplinary HPC in Canada. Their report, anticipated in the fall of 2004, is expected to recommend continuing support for the successful Tier 2 regional consortia and a ramp-up to the establishment of a sustainable national Tier 1 facility. The MTRC stresses the importance of engaging the broader HPC community in developing longer-term sustainable national HPC initiatives.

The community consultations that accompanied development of the C3.ca plan clearly recognized the leading role played by Canadian astronomers in driving the use of large Tier 2 facilities, but demonstrated an immediate need for access to a Tier 1 facility. This situation is mirrored in many other countries: fewer than two percent of scientists are astrophysicists and relativists and yet they frequently utilize twenty percent of Tier 1 computing power. These global figures reflect the particular requirements for simulating exceedingly large and complex astrophysical systems. The astrophysics community's immediate unmet need is thus for Tier 1 computing, and this community is ready and able now to operate such a facility. This community already possesses the required infrastructure to accommodate a Tier 1 facility to satisfy the needs of all Canadian computational astrophysics (e.g. at one of the astronomy-focused sites at the established HPC consortia, or at CITA).

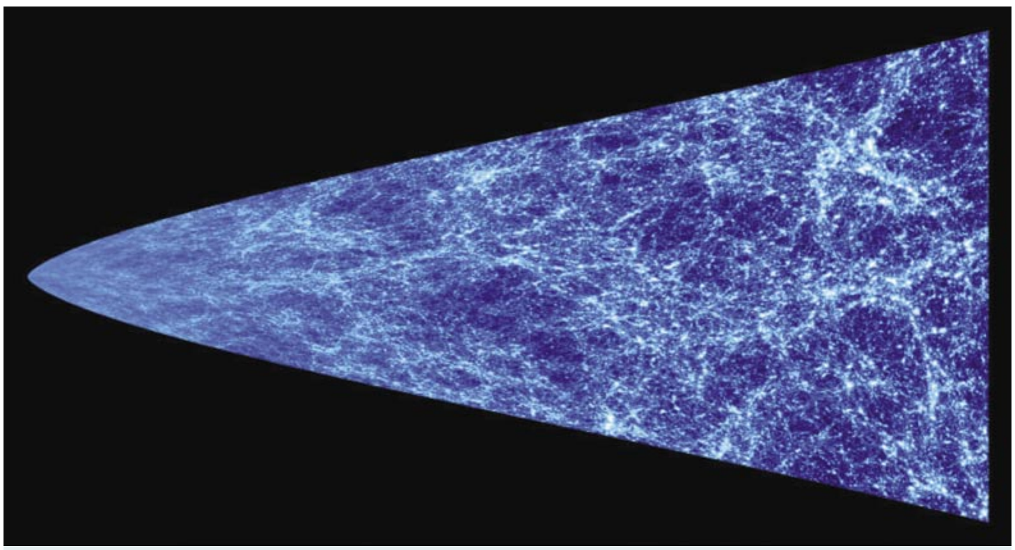

Figure 4.7: This remarkable image shows a computer simulation of the growth of filamentary structure of the Dark Matter in the expanding universe. At the left, the tip of the cosmic bullet represents the Big Bang with time pointing to the right. The envelope shows the growth of the size of a patch of the universe over its 15 billion year history. Galaxies and clusters are seen to be forming at the intersections of the filaments. This simulation was performed with a 512 processor parallel supercomputer at CITA.

Credit: John Dubinski, Department of Astronomy and Astrophysics, University of Toronto

In order to satisfy the immediate demands of the astrophysics community for obtaining and developing a Tier 1 capability, the community of interested researchers should quickly outline a strategy for developing a cost-effective, astrophysics centered Tier 1 system for the next three year technology cycle. This initiative should be accompanied by consultation with C3.ca and other interested researchers outside astronomy to explore the longer term viability of interdisciplinary cooperation at the Tier 1 level. It is anticipated that a system suitable for astronomy would require $15-20M. The skills now existing in Canada provide an outstanding opportunity for astronomy to show leadership in helping to develop a Tier 1 HPC capability for Canada.

The provision of an astronomy-focused Tier 1 HPC facility will pay substantial dividends beyond the astrophysics community in terms of the widely applicable software and expertise for these large and challenging systems, and in encouraging wide interdisciplinary cooperation in Tier I HPC for the longer term.

While the forgoing discussion deals only with Tier 1 level computing, it is worth noting that the third LRP recommendation, dealing with the increase in NSERC equipment grants for desktop computing for data analysis and theory, has not yet been followed. The MTRC wishes to re-iterate this need, and suggests this issue be covered by action on the second MTRC recommendation of section 4.6A.

Accordingly, the MTRC makes the following recommendation concerning Tier 1 level computation:

The MTRC recommends that the HPC community urgently develop and implement a strategy for providing access to a cost-effective Tier 1 computing system for astrophysics, i.e. one which is competitive with the leading systems over all disciplines worldwide. The emphasis should be on covering the need for the next three-year technology cycle. The strategy must ensure access which satisfies the demand of its theoretical astrophysics community, and ensure a national leadership role for this community in computing and an international leadership role in the science achieved. Concurrently the community should engage in a cross-disciplinary dialogue with the aim of ensuring long-term sustainability for Tier I HPC.

4.7 Education and Outreach

The following recommendations were made concerning outreach activities in the LRP:

The LRPP strongly recommends that a significant portion (1.5 percent) of any project budget be allocated towards the support of related outreach efforts. This should be one of the highest priorities among the outreach initiatives. The NRC and the CSA should maintain modern visitor centres that would further aid in the education and enjoyment of the public and the media.

The LRPP strongly recommends that a concerted and sustained effort be made to establish a multi-tiered, effective outreach program that encompasses the public, educational institutions, amateur groups, planetariums, government, and the media. The Canadian Astronomical Society (CASCA) and the NRC, should create a state-of-the-art astronomical website. This should be one of the highest priorities among the outreach initiatives.

The LRPP recommends that CASCA play a steering role in the area of educational outreach to schools. It should allocate resources towards providing workshops and tools for teachers, maintaining a related website, and establishing a budget that could support an information officer who could coordinate these activities.

The LRPP recommends that NSERC maintain and expand its Summer Undergraduate Awards.

The MTRC is pleased to note that public interest in astronomy in Canada remains high. For example, public attendance at Canadian planetariums increased by more than 11 percent to at least 800,000 per year between 2000 and 2003, and there has been a significant increase in membership of the Royal Astronomical Society of Canada (RASC). It is also gratifying to note the recognition received by the RASC for its outreach programs. In 2003 it was a winner of NSERC's Michael Smith Award for sustained and outstanding achievements in science promotion. Furthermore, in Ontario astronomy is now a compulsory "unit" in the grades 6 and 9 science curriculum, and there is an optional course in Earth and Planetary Science at the grade 12 level. The situation is broadly similar elsewhere in Canada. Last but not least, Education and Outreach has now become firmly entrenched in the meetings and newsletter of CASCA, an important step in encouraging younger members to contribute in this area.

It is also a pleasure to note that significant progress has been made in responding to the LRP recommendations in this area, though much remains to be accomplished. Referring to the first LRP recommendation, the target of 1.5 percent of project budgets for related outreach efforts has not been reached. However, NRC did respond in part to this recommendation by establishing the "Centre of the Universe", a 660 square metre modern visitors centre at the DAO. The facility is equipped with a STARLAB planetarium, a 70 seat theatre, displays about Canadian astronomy, and some interactive exhibits. The CSA too is investing about $25K per year in education and outreach on the Canadian space astronomy program.

Regarding the second and third LRP recommendations, there has been progress here as well, due primarily to the efforts of CASCA's subcommittee on Education and Outreach and the efforts of NRC-HIA. CASCA received grants from the NSERC PromoScience Program and from the Ontario Youth Science and technology Awareness Program to support major new initiatives in astronomy education in Canada. These funds were supplemented by CASCA's own funds and funds contributed by the WESTAR Corporation. Among the activities supported by these funds are a bilingual education website aimed primarily at grade 6-9 teachers, development of resource materials for the website, a program of teachers' workshops at CASCA annual meetings, and increased cooperation with planetariums and science centres to promote Canadian astronomy. NRC-HIA also maintains a vigorous outreach program, including a series of weekly articles in both official languages on its own website and talks and guided tours of its own facilities, for example.

These are the highlights, but there are many other outreach activities being undertaken by CASCA, NRC-HIA and individual university departments, and plans exist to continue and expand these activities, which the MTRC heartily endorses. The MTRC also re-emphasizes that much more is required to achieve the LRP goals, and that this needs to be catalyzed by the addition of the resources advocated by the LRPP.

The MTRC considers that the highest priority should be attached to developing and operating a website dedicated to the most exciting developments in results emerging from worldwide research facilities, but with emphasis on Canadian contributions. This website should be authoritative, visually striking, and easy to use. It should rank among the top astronomy websites worldwide, and accordingly it will need to be dynamic, with frequent updates. It should focus on information of interest to the general public and be strongly associated with the CASCA education website for teachers, without duplicating CASCA's effort. It should be the website that the Canadian media automatically turn first to learn about Canadian involvement in the most recent developments in astronomy. Such a website will require maintenance daily by staff fully dedicated to this purpose. Because of the resources required, it should be hosted, developed, and maintained by one of the Canadian universities, in consultation with CASCA, using a portion of the recommended 1.5 percent of project funds directed toward outreach activity. A host institution and a mechanism for managing these funds will need to be identified.

To summarize:

The MTRC commends both CASCA and NRC-HIA for conducting a vigorous and successful program of education and outreach and **recommends**, in accordance with their existing plans, that this program be maintained and expanded.

The MTRC re-iterates the need for 1.5 percent of funds for each telescope or HPC project to be directed toward related outreach activity, and **recommends** that the first priority on such funds be to establish the authoritative and visually striking website recommended by the LRPP. **The MTRC furthermore recommends** that this site be maintained by the necessary full-time outreach staff, supported from the aforementioned funds recommended in the LRP. The management of the website should involve consultation with NRC-HIA, CASCA, CSA and ACURA. CASCA should assist in identifying a mechanism for administering the needed support and in identifying the host for the website.

4.8 Expenditures and Cost Estimates

A. Basic outline

The cost estimates for the projects described in this document are given in Tables 2 and 3. Table 2 is divided into two parts permitting a comparison of the amounts recommended in the original LRP with those recommended by the MTR. The first part entitled "Long Range Plan" shows the amounts recommended in the original LRP document. The second part entitled "Mid-Term Review" shows the amounts spent and/or allocated for the first five years of the LRP, plus amounts recommended (where available) for two succeeding five year periods. All figures under "Mid-Term Review" are in current (2004) Canadian dollars, with no inflation applied, and an exchange rate US$1 = C$1.43 was used to convert US to Canadian dollars. The format of the table is similar but not identical to the corresponding table in the LRP document. Please refer to section 4.8B, **Assumptions and Notes for Table 2** for all items marked with an asterisk.

We draw particular attention to some of the complications associated with the phasing of the various ground-based projects with respect to the LRP cycles of five years. Such complexities were not envisaged in 2000, but now need to be represented since they reflect the realities of implementing the LRP. First, LRP funding did not begin until 2002-03, and some ongoing projects were funded for only three years, ending in 2004-05. Thus the MTR column for the first five years is split into two parts: "Existing" and "New". "Existing" refers to funds from the existing LRP allocation. "New" refers to funds that need to be raised mostly in 2005-06 to continue project development and initiate urgent LRP priorities. The new funds will cover a period of less than five years. For space astronomy "New" reflects MTRC recommended amounts in addition to CSA planned expenditures. Second, the number of funding sources for ground-based astronomy has expanded to include CFI, provincial government matching, and possibly other sources. In later years of the MTR budget period, the sources and distribution of funds remain to be determined, prompting a category "TBD".

The estimates for the JWST, Herschel/Planck and other space astronomy projects are based on figures provided by the CSA covering the period 2000-01 to 2009-10. Figures listed for 2007-11 therefore do not include expenditures in 2010-11 and 2011-12 for which no estimates were available. Also, the tables do not reflect expenditures for 2000-02, which amounted to $1.2M for JWST, $1.7M for Herschel/Planck, and $7.9M for all other projects. The tabulated expenditures for space astronomy are consistent with the LRP, and are endorsed by the MTRC. We note that additional amounts have been added for the recommended postdoctoral fellowship and education/outreach programs starting in 2005-06 under the heading "New".

Table 3 gives a summary of the expenditures recommended for the next phase of the LRP covering the period 2005-11. The figures for ground-based astronomy under "Start 2005" correspond to "New" under the heading 2002-06 in Table 2, and are required soon to continue existing projects and implement LRP priorities. A total of $69M is required in this category. The total for the second five year period of the LRP (2007-11) amounts to $167M. Thus the total amount required for ground-based astronomy for the seven year period 2005-06 through 2011-12 is $236M including all potential sources of funding. The amount for space astronomy is $87.9M, after allowance for the recommended post-doctoral fellowships and public outreach program.

B. Assumptions and Notes for Table 2

All figures in Table 2 representing projected costs show the total amounts, and do not allow for savings afforded by potential reductions in operation costs of the JCMT and CFHT if Canadian involvement these telescopes is reduced or terminated. References to specific table entries below correspond to asterisks in the table.

Existing and New Funds:

The amounts for ground-based astronomy under the heading “Existing” reflect existing allocations to be disbursed during the first five years of the LRP. The amounts shown in the column headed “New” correspond to new funds required starting 2005-06. They are necessary to continue ongoing project studies whose financial support expires before the end of the current five year funding period (e.g. the LAR Phase B Study) and to implement important LRP priorities. For space astronomy, “New” refers to funds recommended by the MTRC starting in 2005-06 in addition to planned expenditures by the CSA under “Existing”.

EVLA:

Funding the EVLA correlator was a condition to secure Canadian access to ALMA under the NAPRA agreement.

SKA:

The figure of $9.5M for the Phase B Study is the amount required for a four year period beginning in 2005-06. The figure $15M is the size of the envelope recommended for building one or more prototypes of SKA components after the international decision is made on the SKA technology. The entry “TBD” reflects the fact that no estimates are yet available for Canada’s share of the construction of the SKA.

TMT DDP Study:

The $6M matching funds required to secure the CFI award of $4M for the TMT DDP study are being sought from the provinces of Ontario and British Columbia, from the NRC-HIA, and from industry contributions. The Canadian contribution to the DDP needed to maintain a 25 percent share is approximately C$25M. Hence a further $15M must be identified soon.

TMT Construction:

In addition to the amount for the DDP ($25M), approximately C$225M is required for a 25 percent Canadian share of the construction of the TMT. This amount has been split between the periods 2007-11 and 2012-16 as $100M and $125M respectively. This ratio is very approximate, however, since the precise division of funds into these two periods is not yet known.

TMT Operations:

This is the estimated Canadian share of operation costs for the TMT for the two year period 2015-2017, following the beginning of science operations after "first light" estimated for 2015. The estimated contribution from Canada is based on a 25 percent share of the annual operational costs, taken to be ten percent of the capital cost.

Gemini/JCMT/CFHT:

The budget figures for Gemini/JCMT/CFHT are, in fact, for Gemini alone. No new LRP funds are recommended for the JCMT or CFHT. Recall from the MTR recommendations on the CFHT and JCMT that support for these telescopes should be transferred to help meet the operating costs of new LRP facilities when Canada's commitments to CFHT and JCMT are ended. The $15M for 2002-06 is the Canadian share of an assumed US$70M instrumentation program for Gemini. These funds will be required for a five year period beginning in 2006. The figure of $6.3M is the estimate for the Canadian share of the increase in operations cost associated primarily with extended queue and service observing at Gemini, and with other Observatory development issues.

HIA Research Staff:

The amounts are required for an increase in research staff complement above pre-LRP levels to reach a total of ten members by 2011-12. This is an increase by four over the six recommended by the LRP. The staff numbers are assumed to ramp up linearly from the LRP recommended complement of six in 2006-07 to ten in 2011-12. The figure under "New" corresponds to new funding required for the two fiscal periods 2005-06 and 2006-07 to bring the LRP funded staff complement up to six from the current level.

Herzberg Fellowships:

The amounts are required for the six post-doctoral fellowships recommended by the LRP plus an additional four to give a total of ten by 2011-12. The increases are assumed to be implemented using the same assumptions regarding the timing as used for the HIA research staff.

NSERC/CSA Fellowships:

The amounts are required for the six post-doctoral fellowships recommended by the LRP plus an additional four to give a total of ten by 2011-12. The increases are assumed to be implemented using the same assumptions regarding the timing as used for the HIA staff and Herzberg Fellowships, except for allowance for the existing CSA Fellowship (assumed to be one for astronomy). The early development of this program starting in 2005-06 is reflected in the category "New".

CADC:

The figures for the CADC include continuing support for salaries plus an increment in 2007-11 to $3M to enable significant equipment upgrades.

HPC:

The figure of $15M for HPC is the estimated cost of establishing a Tier 1 computing facility for astrophysics covering a technology cycle of three years. Although the source of funding cannot be identified, this project would qualify under CFI for both capital and operating support for three years.

Education and Outreach:

The amounts are based principally on the assumption that the costs of education and outreach will be met by applying 1.5 percent of the costs of all telescope or HPC projects.

Table 2: Estimated costs and expenditures from the LRP and MTR (millions of dollars)

	Item	LONG RANGE PLAN				MID TERM PLAN				
		Source	2001-05	2006-10	2011-15	Source	2002-06		2007-11	2012-16
							Existing*	New*		
World Facilities	ALMA Construction	NRC	24.5	23		NRC	16.3		12	
						CFI	7.9			
	EVLA*					NRC	20			
	ALMA Operations	NRC		2.5	10	NRC			10	20
	SKA Studies*	NRC	3.4	8.5	1	NRC	2.4	9.5	15	
	SKA Construction	NRC			30	TBD				TBD
	VLOT Studies	NRC	22.4	22.4		NRC	4.3			
	VLOT Construction	NRC			30					
	TMT DDP Study*					CFI		4		
						Match (TBD)		6		
						TBD		15		
	TMT Construction*					TBD			100	125
	TMT Operations*					TBD				50
	JWST	CSA	38	38		CSA	31.3		36.4	
Moderate Projects	Herschel/Planck	CSA	9.5	9.3		CSA	13.6		5.3	
	Space VLBI/other	CSA	1	1		CSA	16.8		9.3	
	Gemini/JCMT/CFHT*	NRC	3.5	8	5	NRC	6.4	15	6.3	6.3
	MegaPrime	NRC	0.5	0.6						
	WIRCAM	NRC	3.8							
	Receiver Group	NRC	1	1	1	NRC	1		1	1
	Correlator Group	NRC	1	1	1	NRC	1.1		1	1
	CGPS Extension	NRC	2.6			NRC	0.53			
	DAO Telescopes	NRC	0.5	0.5	0.5	NRC	0.25		0.25	0.25
People	HIA Research Staff*	NRC	3	3	3	NRC	1.9	0.34	4	5
	Herzberg Fellowships*	NRC	1.7	2.1	2.1	NRC		0.42	2.8	3.5
	CSA Fellowships*	CSA	0.85	1.05		CSA	0.12	0.09	1.4	1.7
	NSERC Fellowships*	NSERC	0.85	1.05	1.05	NSERC		0.21	1.4	1.7
	Exp. Astro. Labs	NSERC	3.5	3.5	3.5	NSERC		1.4	3.5	3.5
	Research Grants	NSERC	1.5	1.5	1.5	NSERC		0.6	1.5	1.5
Computing	CADC (CVO)	NRC	1.5	1.5	1.5	NRC	1.56		3	1.75
	HPC (Tier 1 facility)	NRC	1.5	0.5	0.5	TBD		15		
	Equipment Grants	NSERC	2.5	2.5	2.5	NSERC		1	2.5	2.5
E&O	Education & Outreach*	NRC	0.9	0.9	0.9	NRC		0.37	0.6	0.4
		CSA	0.6	0.6		CSA	0.13	0.37	0.9	TBD
		CASCA	0.1	0.1	0.1	CASCA	0.11		0.1	0.1
						TBD		0.45	1.5	TBD
Totals		NRC	71.8	75.5	86.5	NRC	55.7	25.6	56	39.2
		CSA	50	50		CSA	62	0.5	53.3	TBD
		NSERC	8.4	8.6	8.6	NSERC		3.2	8.9	9.2
		CFI				CFI	7.9	4		
		TBD				TBD		36.4	101.5	TBD

Table 3: Recommended Expenditures for the Period 2005-2011 (millions of dollars)

		Priority	Ground-based			Space-based
			Start 2005**	2007-11	Total	
World Facilities	ALMA	*		22	22	
	SKA	*	9.5	15	24.5	
	VLOT/TMT	*	25	100	125	
	JWST	*				60.6
	Subtotals		**34.5**	**137**	**171.5**	**60.6**
Moderate Projects	Herschel/Planck	*				8.9
	Other space projects***					15.6
	Gemini	*	15	6.3	21.3	
	Receiver/Correlator groups			2.0	2.0	
	DAO Telescopes			0.25	0.25	
	Subtotals		**15**	**8.6**	**23.6**	**24.5**
People	HIA Research Staff	*	0.3	4	4.3	
	Herzberg Fellowships	*	0.4	2.8	3.2	
	CSA Fellowships	*				1.5
	NSERC Fellowships	*	0.2	1.4	1.6	
	Experimental Astro Labs		1.4	3.5	4.9	
	Research grants		0.6	1.5	2.1	
	Subtotals		**2.9**	**13.2**	**16.1**	**1.5**
Computing	CVO			3.0	3.0	
	HPC		15		15	
	Equipment grants		1	2.5	3.5	
	Subtotals		**16**	**5.5**	**21.5**	
	Education & Outreach		**0.8**	**2.2**	**3.0**	**1.3**
	Totals		**69.2**	**166.5**	**235.7**	**87.9**

* Indicates association with a strong recommendation.

** These funds correspond to column "New" under 2002-06 in Table 2.

*** These projects include BLAST, FUSE, UVIT, CADC support, concept studies and new opportunities.

CHAPTER 5

Funding and Managing Large Astronomy Facilities

The management and financial support of the major ground-based observatories used by Canadian astronomers has been, since 1970, a responsibility of NRC, which has been mandated by Parliament to "operate and administer any astronomical observatories established or maintained by the Government of Canada.". This mandate is executed by NRC-HIA, which also provides most of the expertise in instrument development for large optical and radio telescopes. Thus NRC-HIA supports a broad range of astronomical research, both ground and space-based, involving a wavelength range from the ultraviolet to centimetre, and with the provision of powerful data archiving and retrieval capabilities. The effectiveness of this role of NRC-HIA is readily demonstrated by the new facilities made available to all Canadian astronomers since the early 1970's. Furthermore, its present role and relevance to the community has been amply demonstrated through its research collaborations and through its leading role in the development of new LRP facilities, including ALMA, TMT and SKA. In addition, NRC-HIA makes important contributions to the space astronomy program of the CSA, including essential work on VSOP, FUSE and the JWST. However, the MTR has clearly shown that no existing single agency or organization is able to fund and manage the entire range of facilities recommended in the LRP. Consequently the MTRC believes that it is necessary and timely to consider a new framework for financing and managing large international astronomy facilities in the future.

Support for astronomy facilities is now possible through a variety of organizations in addition to NRC, including NSERC, CFI and the CSA, and these organizations are providing significant opportunities to fund particular aspects of the very large projects in the LRP. However, funding applications must be consistent with the specific mandates of each agency and generally have to conform to agency program constraints that are not necessarily well aligned with the overall project needs. For example, CFI provides capital for infrastructure, but offers only limited operational funding and therefore cannot address the long term needs of a major ground-based observatory, which has a lifetime measured in decades. Thus along with the new opportunities there is an increase in the complexity of securing the necessary funds and possibly in the project management structures. The LRP and the MTR call for a tighter collaboration among the agencies to permit a coherent approach to the funding of the large international astronomical projects that are at the heart of the LRP.

These and other considerations have inspired the formation of ACURA which is emerging as the organization which speaks to the funding agencies with a single voice on behalf of the university community. ACURA, which comprises 21 universities, has a legal and financial structure to enable it to apply for the financial support to develop and manage large projects for the university community. The universities within ACURA also possess significant skills in developing instrumentation, but most of the skills presently lie within NRC-HIA. CASCA speaks for all Canadian astronomers, both government and university, and has been especially effective in planning the future of astronomy in Canada (as their roles in the LRP and the MTR attest). However, CASCA cannot, and should not, apply for funds to build and manage facilities. Clearly the time is ripe for a new national strategy and framework to develop strong national initiatives and international collaborations.

The MTRC regards ACURA as the appropriate choice for the organization to initiate and direct a process to bring coherence and stability to the funding of large and expensive astronomy facilities. Together with CASCA, it should engage the funding agencies and enable a process for this to happen. Furthermore, it should happen very soon to permit an effective engagement of the Federal Government in the support of the large projects within the LRP.

In summary:

The MTRC recommends that ACURA, in consultation with CASCA, undertake as one of its missions to develop and review models for establishing a new structure for developing and managing large facilities for Canadian astronomy. There should also be consultation with the relevant agencies, NRC-HIA, NSERC and the CSA. Account should be taken of the need to preserve the existing strengths within Canada (e.g. NRC-HIA), and to provide flexibility for individual university researchers within or outside ACURA to pursue their own astronomy projects. One of the central issues should be a stable and effective mechanism for funding the capital and operating phases of large international astronomy projects and facilities.

CHAPTER 6

Economic Impact

As anticipated in the original planning document, implementation of the LRP is having a strong economic impact due to the extensive involvement of the private sector and universities in every major project. In the case of ALMA, NRC-HIA intends to contract the fabrication of the required set of commissioning receivers operating at 3mm wavelength to a Canadian company. Certain aspects of this work have commercial applications in the telecommunications industry, and the transfer of technical know-how from NRC-HIA to the private sector is expected to boost competitiveness and lead to new business opportunities. At the time of writing, several companies have responded to the call for expressions of interest and an initial contract for production of low-noise amplifiers developed by NRC-HIA for ALMA has been let. In a statement that could be applied to all LRP projects, the Vice President of AMEC Dynamic Structures Ltd. said: "ALMA is a big shot in the arm for Canadian astronomers and the Canadian astronomy industry." A good example is DiCOS Technologies, a Quebec City manufacturer of high performance laser systems who were selected to provide the Master Laser system for ALMA. The company noted that this is a unique product that will significantly improve their stabilized laser portfolio. The EVLA correlator is based on the patented WIDAR technology developed at the DRAO but the fabrication of the correlator components will be done by industry.

Development of the LAR is being conducted with the contracted assistance of AMEC Dynamic Structures Ltd. (ADSL), of Port Coquitlam, BC, who fabricated an operating prototype section of the adaptive reflector surface. This work has thus made important strides toward demonstrating the feasibility of the LAR as an element of the SKA. As this report is being prepared, discussions are underway with firms in the photonics sector that can assist in the very challenging development of the large focal plane array subsystem needed for the LAR. Focal plane arrays are the equivalent of digital cameras at radio frequencies and the successful pursuit of this technology will open many new commercial opportunities. ADSL entered the astronomy business some 30 years ago through a relatively modest contract to build the CFHT dome and has now become the premier company in the world for this specialized work but, more significantly, has been able to use its astronomical experience to enter a much bigger business - the building of dynamic structures (theme rides) for the entertainment industry. This evolution continues today and ADSL has been intimately involved not only in the LAR but also in the VLOT/TMT program.

On 14 September, 2004, AMEC announced the award of a US$3.8M contract to ADSL to design and build the Atacama Cosmology Telescope (ACT). The ACT is an optimized mm wave telescope with an aperture of six metres designed to study the CBR with unprecedented sensitivity and resolution, leading to a comprehensive understanding of the formation of cosmic structure. The ACT involves an extensive collaboration of North and South American institutions, including two Canadian universities. Its automated operation under the severe conditions atop the Atacama 5200 metre plateau in Chile places stringent engineering requirements on its design, and the award of this contract to ASDL is a testimony to Canadian prominence in the design and fabrication of large precision structures.

In the area of precision optics, the National Optics Institute, INO (Quebec) has been contracted to study development of the advanced, super-durable coatings needed for the TMT mirrors.

In the LRP, it was noted that an independent economic study of the investments made by Government in astronomical facilities leads to a benefit/cost ratio of about 2:1. It is too early to make such a detailed assessment of the current investments in the LRP but it is clear from the evidence cited above that there is every reason to expect a similar positive economic return for the current round of development activities.

In space astronomy, contracts are let by the CSA to the Canadian aerospace industry. The recipient of the largest of the astronomy contracts is EMS Technologies Inc. (Ontario) for JWST, with subcontracts to ComDev (Ontario). Other examples of industrial involvement include FUSE and MOST, involving contracts to ComDev and Dynacon Inc. (Ontario) respectively, and UVIT, for which the phase A contract is held by Routes Inc. (Ontario).

Research and development related to the LRP are also being conducted at nearly every major university in Canada, including the University of Victoria, University of B.C., University of Alberta, University of Lethbridge, University of Calgary, University of Waterloo, University of Toronto, University of Montreal, McGill University and Laval University. During 2003-04, 46 science and engineering students from 12 universities gained experience at NRC-HIA facilities while working on projects supported largely by LRP funds. Accordingly, implementation of the LRP is extremely successful to date in training HQP, which in turn will further strengthen the base of Canadian scientific and technical capability.

It is clear that the LRP, taken in its entirety, will significantly enhance high technology capacity, both in the private sector and in the universities, and will contribute to Canada's competitiveness internationally.

CHAPTER 7

Acronyms and Abbreviations used in this document

ACT	Atacama Cosmology Telescope
ACURA	Association of Canadian Universities for Research in Astronomy
ADSL	AMEC Dynamic Structures Ltd.
AGM	Annual General Meeting
ALMA	Atacama Large Millimeter Array
ALTAIR	ALTitude-conjugate Adaptive optics for InfraRed
AUI	Associated Universities Incorporated
AURA	Association of Universities for Research in Astronomy
BAM	Balloon-borne Anisotropy Measurement
BLAST	Balloon-borne Large Aperture Sub-millimetre Telescope
CAD	Computer Aided Design
CADC	Canadian Astronomy Data Centre
Caltech	California Institute of Technology
CASCA	Canadian Astronomical Society
CBR	Cosmic Background Radiation
CCA	Coalition for Canadian Astronomy
CFHT	Canada-France-Hawaii Telescope
CFHTLS	CFHT Legacy Survey
CFI	Canada Foundation for Innovation
CGPS	Canadian Galactic Plane Survey
CSA	Canadian Space Agency
CVO	Canadian Virtual Observatory
DAO	Dominion Astrophysical Observatory
DDP	Detailed Design Phase (for the TMT)
DRAO	Dominion Radio Astrophysical Observatory
ESA	European Space Agency
ESO	European Southern Observatory
EVLA	Expanded Very Large Array
FCRAO	Five Colleges Radio Astronomy Observatory
FGS	Fine Guidance Sensor (for JWST)
FUSE	Far Ultraviolet Spectroscopic Explorer
GSMT	Giant Segmented Mirror Telescope
GMOS	Gemini Multi-Object Spectrograph

HARP-B	Heterodyne Array Receiver Program-B band (325-375 GHz)
HEA	High Energy Astrophysics
HQP	Highly Qualified Personnel
HPC	High Performance Computing
HST	Hubble Space Telescope
IGPS	International Galactic Plane Survey
ISI	Institute for Scientific Information
IVO	International Virtual Observatory
JCMT	James Clerk Maxwell Telescope
JCSA	Joint Committee on Space Astronomy
JWST	James Webb Space Telescope
LAR	Large Adaptive Reflector
LRP	Long Range Plan
LRPP	Long Range Plan Panel
MERLIN	Multi-Element Radio Linked Interferometer Network
MOST	Micro-variability and Oscillations of Stars
MOU	Memorandum of Understanding
MTR	Mid-Term Review
MTRC	Mid-Term Review Committee
NAPRA	North American Program in Radio Astronomy
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NRAO	National Radio Astronomy Observatory
NRC	National Research Council (of Canada)
NRC-HIA	National Research Council–Herzberg Institute of Astrophysics
NSERC	Natural Sciences and Engineering Research Council (of Canada)
NSF	National Science Foundation
RASC	Royal Astronomical Society of Canada
SCUBA	Submillimetre Common User Bolometer Array
SCUBA-2	SCUBA – second generation
SETI	Search for Extra-Terrestrial Intelligence
SKA	Square Kilometer Array
TBD	To Be Determined
TMT	Thirty Meter Telescope
UC	University of California
UVIT	Ultraviolet Imaging Telescope
VLA	Very Large Array
VLOT	Very Large Optical Telescope
VSOP	VLBI Space Observatory Program
WF8m	Wide Field Eight Metre Telescope
WIDAR	Wideband Interferometric Digital ARchitecture
WMAP	Wilkinson Microwave Anisotropy Probe

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What is now proven was once only imagined

William Blake