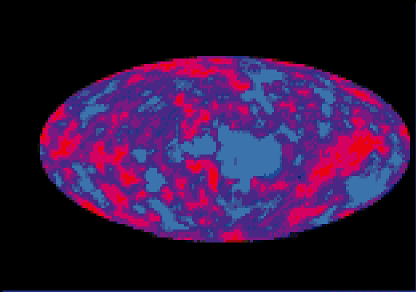
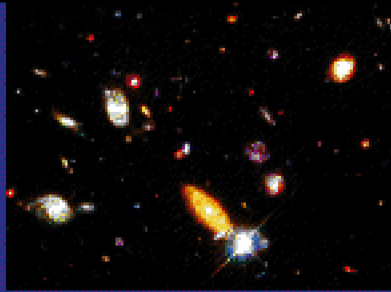
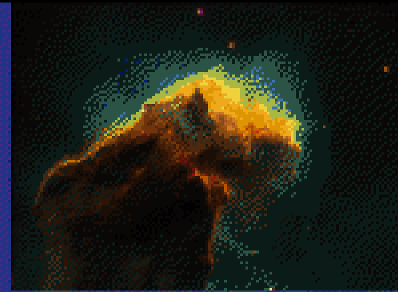
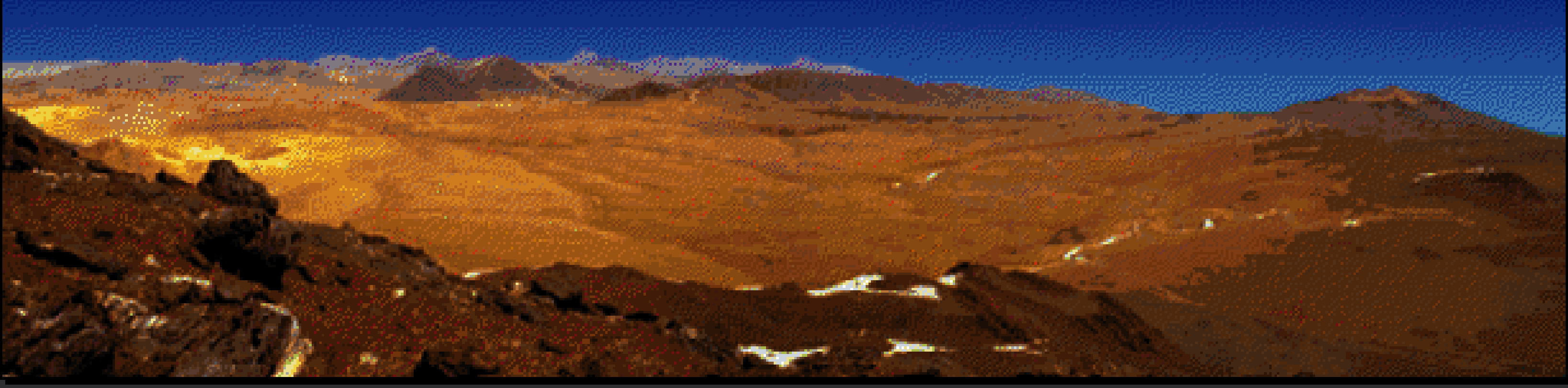





CANADIAN ASTRONOMY AND ASTROPHYSICS IN THE 21ST CENTURY

THE ORIGINS OF STRUCTURE IN THE UNIVERSE

Report of the NRC-NSERC Long Range Planning Panel



Preface

Astronomy and astrophysics are fields that are undergoing tremendous growth as a consequence of three decades of scientific, technological, and instrumental breakthroughs. Canadian astronomers have made key contributions to the golden age of astronomy that is now upon us.

The coming two decades will see the development of new types of observatories both on the ground and in space that will catapult to new levels, our knowledge of everything from the formation of planetary systems, stars, and galaxies,to the structure of the universe itself. Our investment in this truly exciting age of cosmic exploration will have benefits for many areas of fundamental astronomical and scientific research, public education and culture, and technological and industrial development. More than ever, a process to develop a unified vision for the new astronomical research facilities over the next 10-15 years is needed. This goal led to the commissioning of a panel, in the summer of 1998, whose charge was to develop a comprehensive view and decadal program for astronomy and astrophysics in Canada. Fundamental to this process is the requirement that the vision articulated in the plan truly reflects the needs of the Canadian astronomical community as a whole and represents the consensus of our community.

The Long Range Planning Panel (LRPP) was established by the National Research Council (NRC) and the Natural Sciences and Engineering Research Council (NSERC) with the full participation of the Canadian Astronomical Society (CASCA). The chair was selected in mid July of 1998, and the membership of the panel developed with the full participation of all threeagencies over the next month. The seven member panel consists of Ralph Pudritz (Chair, McMaster University), Andrea Dupree (Harvard-Smithsonian Centre for Astrophysics), William Harris (McMaster University), Gilles Joncas (Université Laval), Simon Morris (NRC's

Herzberg Institute for Astrophysics), Ernie Seaquist (University of Toronto), and Jack Welch (University of California at Berkeley). The formal mandate of the LRPP (posted on LRPP web site) was communicated to it in August, and made available to the community in early September, 1998.

The LRPP developed many mechanisms to ensure that the community was fully engaged in the planning exercise. The HIA established, for the LRPP, a web site http://www.hia.nrc.ca/lrpp/ on which public discussion and comment on the plan could be made, and at which all of the preliminary papers, announcements, and early versions of the plan were posted. Five separate subcommittees of CASCA (radio, optical and infrared, space, theory, and education), plus one additional ad hoc committee on computation were consulted in order to provide the LRPP with advisory reports on issues within their respective areas. In addition, the LRPP solicited advisory papers from many other groups within our community. These provided more detailed examination of specific projects such as a Canadian Large Adaptive Reflector (CLAR), the Next Generation Space Telescope (NGST), a wide-field 8 metre optical/infrared telescope, etc. A subset of these advisory papers constitutes Volume II of our report, which is posted on the LRPP web-site. All of these subcommittees and other groups began their work in September 1998, and submitted their papers to the LRPP by mid-February, 1999. A third way of interfacing with our community was through a series of town hall meetings that were held across the country; at the Université de Montreal (Dec. 2, 1998), the University of Toronto (Dec. 5, 1998), the University of Calgary (Dec. 14, 1998) and the University of Victoria (Dec. 15, 1998). A total of more than 160 astronomers participated in these town hall meetings, each of which consisted of both open presentations and discussion sessions, as well as the opportunity for many private interviews and discussions with the panel for anyone who wished. The panel met in early September and November 1998, and mid-February 1999 at McMaster University, as well as in late December 1998 at the HIA in the wake of the completed town hall meetings.

Various members of our community as well as international experts in specific areas of astronomy were invited to make presentations to the panel during these meetings. A series of e-mails outlining the preliminary findings of the panel were sent out to the community following the LRPP's 3-day policy meeting in mid-February which allowed the community the opportunity to gain an impression of how the community plan was developing. A draft of the plan was circulated for comments to members of the HIA and CASCA Boards in late May, as well as to the entire community in early June. The final document was prepared after the annual CASCA Meeting in Halifax in late June, 1999, when the community participated in a final and extensive, open discussion of the draft. In summary, the LRPP went through tremendous lengths to ensure that this planning process involved and consulted with the community at many different levels.

The LRPP appreciates the time and effort that our community has contributed towards making this exercise a success. We were impressed by the enthusiastic and substantial community response and participation in our deliberations. Our panel has found that sufficient time must be set aside in order to let ideas develop and reach fruition during such an ambitious planning exercise; a full year should be set aside ideally bracketed by two summer CASCA Meetings. There is a great depth of design and purpose in this plan that has repercussions far outside the immediate area of astronomy and astrophysics in Canada over the next decade. The LRPP believes that this kind of decadal planning exercise provides a valuable means of developing a long range vision of our needs throughout the decades to come.

There are many people to thank for their unstinting help and wise counsel over this last year. The panel is grateful for the efforts of the advisory committees and thanks their chairs in particular for the timely preparation of their reports. Likewise, we thank the authors of the many advisory papers for their thoughtful written reports and detailed studies. Many readers gave us interesting suggestions and comments on early drafts of the text and we thank all the writers of those many, many e-mails for their advice. We thank the members of the HIA Advisory and CASCA Boards, Jim Hesser, and Tom Landecker for their written comments on the draft as well. Don Morton (NRC, Director General HIA), Michael de Robertis (CASCA President), and Kate Wilson (NSERC) provided us with invaluable resources and comments at many points along the way. We thank Eugene Martinello (Creative Services Supervisor, McMaster) and his staff for their imaginative production of this volume. In addition, Patricia Monger (CIS, McMaster) provided us with excellent computer assistance throughout this exercise, and Robert Hay (McMaster) and Robert Lamontagne (Montréal) helped us to design a successful public outreach effort that unfolded during the course of the year.

Finally, I am grateful for the wisdom, energy, commitment, and scientific depth that all members of the LRPP constantly displayed throughout this arduous, but rewarding, undertaking.

Ralph E. Pudritz,
Chair
Long Range Planning Panel
McMaster University, August, 1999.

CHAPTER 1

Introduction and Executive Summary

Astronomy began millennia ago when the first humans looked up at star-laden skies. Our wonder at the cosmos, which appears in every culture in history, has been the source of our deepest discoveries about the nature of the universe and our place within it. The impact of astronomy upon science and culture has been profound and is strongly linked to both cultural and technological advances.

Today we live amid the most remarkable age of astronomical discovery in history. The 20th century began with a picture of a tiny static universe, and is ending with evidence that the rate of its vast expansion may be accelerating. It began with knowledge of only our own galaxy of stars, and is ending with the discovery that the many billions of galaxies that make up our universe originated approximately 15 billion years ago from the progressive merger of much smaller entities. It began with no means of answering the centuries old question: are there other solar systems in the universe? and is ending with the spectacular discovery of the first true planetary system around another star. The instruments and observatories that will appear in the early 21st century promise to reveal how planets and stars assemble, how galaxies appear and grow in the universe, how the first stars appeared in our universe, and what the structure of our universe actually is. The central theme of astronomy in this new era will be elucidation of the origins of structure in the universe, from planets to the universe itself.

The sole aim of science is the glory of the human spirit.

Gerhard Herzberg,
Canadian Nobel Laureate
in Chemistry

Canadian astronomers have contributed strongly to this international voyage of exploration. By almost any reckoning, our community ranks among the top three nations in the quality of its astronomical research per capita. The Canada-France-Hawaii Telescope (CFHT) on Mauna Kea in Hawaii was arguably the world's best optical telescope in the last decade. The James Clerk Maxwell Telescope (JCMT) is today making some of the most important new discoveries in radio astronomy. The Canadian Institute of Theoretical Astrophysics (CITA) is one of the world's leading astrophysical research centres. Canada's partnership in the twin, Gemini 8 metre class telescopes will contribute to making them among the best in the world. The Canadian Space Agency is poised to make Canada an important player in the Next Generation Space Telescope (NGST), the successor to the Hubble Space Telescope. In all of these scientific and technical projects, the return to Canada's economy, through contracts to high technology Canadian firms and institutes, is far greater than our original investment. The National Research Council (NRC) has played a central role in designing and operating the marvelous set of observatories that are used by astronomers all across the country.

What should Canada's priorities be in this golden age of astronomy and astrophysics?

The NRC-NSERC Long Range Plan is the fruit of extensive consultation in 1998 and 1999 with all facets of our Canadian astronomical community. The recommendations of the Long Range Planning Panel (LRPP) represent the consensus of our entire astronomical community for its priorities in astronomy in the coming 10-15 years. We present a unified vision of astronomy and astrophysics that emphasizes the need to construct a complementary set of ground and space-based observatories. The very complexity of the origin and evolution of structures in the universe implies that no single telescope can be the complete tool with which to address these problems; a carefully designed, interwoven and complementary set of observatories is required. This vision includes participation in newly emergent world observatories, as well as international and national observatories; growth in the research capabilities of our leading institutes and universi-

The Large Magellanic Cloud (LMC), a small satellite galaxy near our own Milky Way, is the site of considerable active star formation. This Hubble Telescope view of one corner of the LMC shows a brilliant, densely populated young cluster of stars surrounded by the wispy traces of gas and dust from which it emerged.

Image by Hubble Heritage Team (AURA / STScI / NASA ties; extensive investment in the training and support of the most talented young scientists; the development of important public and educational outreach programs; the inspiration of the younger generation to enter technical fields; and the stimulation and participation of many Canadian high-technology firms and industries.

This report argues that Canada will need to invest 147 million dollars in NRC programs over the next decade, in addition to current funding, if we are to retain our current prominence in international astronomy. It also argues for the importance of investing 100 million dollars, over the next decade, for space-based astronomy programs through the Canadian Space Agency (CSA). Finally, this report makes a case to the Natural Science and Engineering Research Council (NSERC) for investing an additional 17 million dollars over the next decade, in order to support the people and university based research effort that are needed in order to take full advantage of these new observatories. The current investment in astronomy per capita in Canada is less than a dollar per year. This level is seven times smaller than the per capita funding of astronomy in the United States, and five times smaller than in European countries such as Germany, France, Italy, and the UK (see Table 2, Chapter 3). The proposed total new funding will nearly double the total spending by NRC and NSERC on astronomy in Canada, currently at $ 21.8 million dollars per year. This is essential if we are to redress some of the critical shortfall – and ensure that the attendant benefits accrue to Canadian society, especially to its young. The advent of the new world observatories makes such enhanced investment an absolute necessity. If Canada fails to participate in them, our astronomical community will be sidelined within a decade.

This report also shows that this expenditure does not place a burden upon the economy. Quite to the contrary, these programs will garner a direct return to industry and technology in Canada that is several times larger than our initial investment – about a half billion dollars over the next decade. An even larger return is anticipated from far ranging, high-tech spin-offs. Most of the proposed funding will be spent in Canada through contracts to Canadian industries. Our vision for astronomy represents a long term investment in cosmic exploration, in the education and culture of our people, and in the further flowering of our most sophisticated technologies and industries.

The report begins with the foundations of the plan, namely, a description of the exciting, major frontiers in astronomy and astrophysics over the next two decades (chapter 2). It continues with a description of the current status of our observatories and community (chapter 3) and a brief account of the new world and international observatories that will be designed to help solve these fundamental problems in astronomy (chapter 4). We then describe, in detail, the plan for astronomy in Canada over the coming 10 - 15 years (chapter 5). Finally, the report describes the computational (chapter 6), the cultural and educational (chapter 7), and the economic impact (chapter 8) of the plan.

EXECUTIVE SUMMARY

The LRPP considered a large number of worthy proposals for new observatories, instruments, and even institutes. We do not further describe the initiatives that the LRPP decided not to recommend. ***All of the recommendations discussed in this report, described in detail in Chapter 5, are to be regarded as being essential to Canadian astronomy and astrophysics.*** Our recommendations are grouped into two classes, with no further prioritization given to projects within a class. The class given highest priority denotes facilities, projects, and other initiatives whose failure to be funded would lead to particularly severe and permanent damage to our future in the field.

Our recommendations for participation in new major facilities, as well as in moderate size projects and facilities in the next decade are:

• ***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 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.

ALMA and NGST are the two new, first generation world observatories that will appear in 2000-2010. They will be among the key observatories of the next century and have the highest priority in the USA, and European astronomical plans.

• ***The LRPP strongly recommends*** that the Canadian Large Adaptive Reflector (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.

Canada is poised to play a leading role in the second generation of world observatories that will likely be constructed in 2010 - 2020, particularly in the unique and highly innovative LAR design concept for the world Square Kilometre Array (SKA) for centimetre wave radio astronomy.

• ***The LRPP strongly recommends*** that a team be established to develop designs for a Very Large Optical Telescope (VLOT). This study should be one of the highest priorities among moderate size projects. Canada should join a world team in this effort.

Canada should also position itself to be involved with a possible ground-based Very Large Optical Telescope (VLOT) that may be 25 metres in diameter or even more. VLOT will be highly complementary to NGST.

• ***The LRPP recommends*** that a development envelope should also be established that could fund the construction of LAR or VLOT prototypes, if recommended by a rigorous mid course review in approximately five years time.

• ***The LRPP recommends*** that Canada position itself now for entry into the construction of SKA as well as VLOT.

The tetrad of world observatories, with ALMA and NGST appearing in 2000-2010, and SKA and VLOT likely in 2010-2020, will constitute a complementary, and amazingly powerful set of observatories that will be 100 to 1000 times more sensitive than any observatories today, over an immense range of wavelengths. They will enormously advance all of the scientific goals in the search for the origins of structure. They will also all be major stimulants to the development of new technology and industry.

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

These groups will be of central importance in Canada's participation in ALMA and SKA. The NRC should energetically investigate the creation of strong, mutually beneficial, collaborative links with the USA's National Radio Astronomical Observatory (NRAO) as one of the most efficient routes for rapid entry into ALMA. The involvement of the correlator group in NRAO's planned Very Large Array extension would be an excellent use of our expertise in correlators and could serve as a good entry card into ALMA.

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

Gemini will provide exciting capabilities in a forefront telescope in the new 8 – 10 metre era that is upon us.

• ***The LRPP recommends*** that our community quickly obtain significant participation (40 %) in the construction and operation of a new, optical/infrared, 8 metre class telescope. Wide-field capability (WF8m) should be given priority.

In order to keep our community competitive in the era of 8 metre optical and infrared telescope science, a new, wide field of view, 8 metre telescope should be constructed to complement the capabilities of the Gemini optical telescopes which are now coming on line. If a compensating share of a new, wide field 8 metre becomes available, then priority for resources invested in the CFH 3.6 metre telescope should be given to the 8 metre, as needed.

Priority for resources invested in JCMT must be given to support ALMA beyond 2009. The extended Galactic Plane Survey should be supported until 2005.

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

The FIRST/Planck satellite for millimetre astronomy would provide invaluable measurements of fundamental cosmological parameters.

• ***The LRPP recommends*** that an on-going presence in space-based VLBI be maintained through CSA programs.

Our recommendations for the support of people at institutes and universities include:

• ***The LRPP strongly recommends*** that at least six additional staff astronomers, of the highest calibre, be hired for the HIA, in addition to new technical staff. 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 facilitate 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 scientific leadership.

• ***The LRPP strongly recommends*** that high profile, international postdoctoral fellowships of the stature of the NASA Hubble Fellows be established. This should be one of the highest priorities in funding new people:

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

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

• ***The LRPP strongly recommends*** that university laboratories for experimental astrophysics be created. This should be one of the highest priorities among moderate size projects. These could be supported by NSERC, as well as other agencies, and will need commitments of infrastructure and faculty positions from the host universities.

A substantial investment in our research groups at institutes and universities needs to take place in concert with the development of the new facilities, in order to reap the highest scientific returns and to generate much stronger links with technology.

Our recommendations for the support of computational initiatives include:

• ***The LRPP strongly recommends*** that NRC's outstanding CADC develop its ability to manage archives of data from upcoming space and ground-based observatories. Funding should be provided to develop innovative data mining techniques that maximize the scientific usefulness of multi-wavelength observations in astronomy. This should be one of the highest priorities among the computational projects.

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

Our academic computational resources lag far behind those of other nations and require immediate bolstering and support.

Our recommendations for the establishment of vigorous outreach programs include:

• ***The LRPP strongly recommends*** that approximately 1.5 % 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. Furthermore, the NRC and the CSA should create modern visitor centres that would further aid in the education and enjoyment of the public and the media.

• ***The LRPP strongly recommends*** that the Canadian Astronomical Society (CASCA) and the NRC with the participation of the CSA, create a first rank national web site for astronomy. 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 web site, and employing an information officer who could co-ordinate these activities.

It is critically important to develop comprehensive public outreach programs of different kinds. A concerted and sustained effort must be made to establish a multi-tiered outreach program that encompasses the public, educational institutions, amateur groups, the government, and the media.

An overview of the recommendations of the LRPP plan is in Table 1.

Table 1: LRPP Plan: New Funding Requirements (millions $Can)

Category		Item	Funding Source	Priority	2001 -2005	2006 -2010	2011 -2015
Major New Facilities	a) Ground Based	**ALMA**					
		ALMA - studies	NRC	*	1.5	0	0
		ALMA - construction	NRC	*	23	23	0
		ALMA - operation	NRC	*	0	2.5	10
		WF8m					
		WF8m - construction	NRC		16	16	0
		WF8m - operation	NRC		0	0	3
		Prototype Development Envelope (CLAR or VLOT)	NRC		7.5	7.5	0
		SKA					
		SKA - construction of full array	NRC		0	0	30
		VLOT					
		VLOT - construction	NRC		0	0	30
	b) Space Based	**NGST**	CSA	*	38	38	
		FIRST/Planck	CSA		9.5	9.3	
		Space VLBI	CSA		1	1	
Moderate Size Facilities/Projects		SKA - study, phase B (CLAR)+Incr. staff base	NRC	*	3.4	1	1
		VLOT - study	NRC	*	1	3.7	0
		Receiver Group (staff)	NRC	*	1	1	1
		Correlator Group (staff)	NRC	*	1	1	1
		Gemini/JCMT/CFHT Operations	NRC	*	3.5	8	5
		CFHT - Megaprime operations	NRC		0.5	0.6	0
		CFHT - WIRCam	NRC		3.8	0	0
		WF8m - study	NRC		0.5	0	0
		Extension of Galactic Plane Survey	NRC		2.6	0	0
		Enhanced operation of DAO telescopes	NRC		0.5	0.5	0.5
People		Additional HIA Research Staff (6 positions)	NRC	*	3	3	3
		New Herzberg Fellowships (2 new/year, up to 6)	NRC	*	1.7	2.1	2.1
		New CSA/NSERC Fellowships	CSA	*	0.85	1.05	
		(2 new/year, up to 6)	NSERC	*	0.85	1.05	1.05
		Centres for Experimental Asrophysics	NSERC	*	3.5	3.5	3.5
		Increased Operating Grants	NSERC		1.5	1.5	1.5
Computation		Terapix and Data mining	NRC	*	1.5	1.5	1.5
		Mid Level HPC Computing	NRC	*	1.5	0.5	0.5
		Increased Equipment Grants	NSERC		2.5	2.5	2.5
Outreach		Outreach -NRC	NRC	*	0.9	0.9	0.9
		Outreach - CSA	CSA		0.6	0.6	
		Outreach - CASCA	CASCA		0.1	0.1	0.1
TOTALS		NRC			74.4	72.8	89.5
		CSA			50.0	50.0	
		NSERC			8.4	8.6	8.6

C H A P T E R 2

The Origins of Structure in the Universe

We are in the midst of a brilliant era of cosmic exploration. From the discovery of pulsars and quasars in the 1960's, to the detection of other planetary systems and possible acceleration of the universe's expansion in the late 1990's, the pace of astronomical discovery continues to grow. This unprecedented golden age is being driven by the advent of new technologies and powerful, innovative research tools. Telescopes on the ground and in space complement one another and gather signals from across the entire electromagnetic spectrum, while the interpretation and ultimate understanding of these observations is being fostered by increasingly sophisticated theoretical calculations and computer simulations.

What seest thou else in the dark backward and abysm of time?

William Shakespeare, The Tempest (1611)

This chapter outlines some of the major themes of astronomical research that will dominate the first decades of the 21st century. Emphasis is placed on areas in which Canadians have often played significant international roles. The major scientific theme that will run through all of astronomy in the new century is, in essence, the quest for the 'Origins of Structure' in the universe. This quest addresses the formation of planets, stars, and galaxies, as well as the geometry and fate of our universe.

2.1 The Formation of Planetary Systems

How did our own solar system form? How common are planetary systems around other stars, and do any of them resemble ours? And is there life elsewhere? These are among the oldest of human questions. The hypothesis that the Earth orbits the Sun was first proposed nearly 2300 years ago by the remarkable Greek mathematician, Aristarchus of Samos. In the 16th century. Copernicus re-introduced the correct physical picture of the solar system as a set of planets orbiting the Sun, but did not extend the same concept to other stars. Two and a half centuries later, Immanuel Kant introduced the idea that the Sun and planets could have formed by condensing out of a great rotating disk of gas and dust. Today, we know that the gaseous disks that Kant could only speculate about are in fact frequently found around most, if not all, young stars forming in the Milky Way. Within this last decade of the twentieth century, we

Jupiter, the giant of our Solar System, is seen here through the eyes of the Hubble Space Telescope. In the foreground is one of its satellites, Io, casting its shadow (the dark circle at center) on Jupiter's cloudtops. Io is the same size as Earth's Moon.

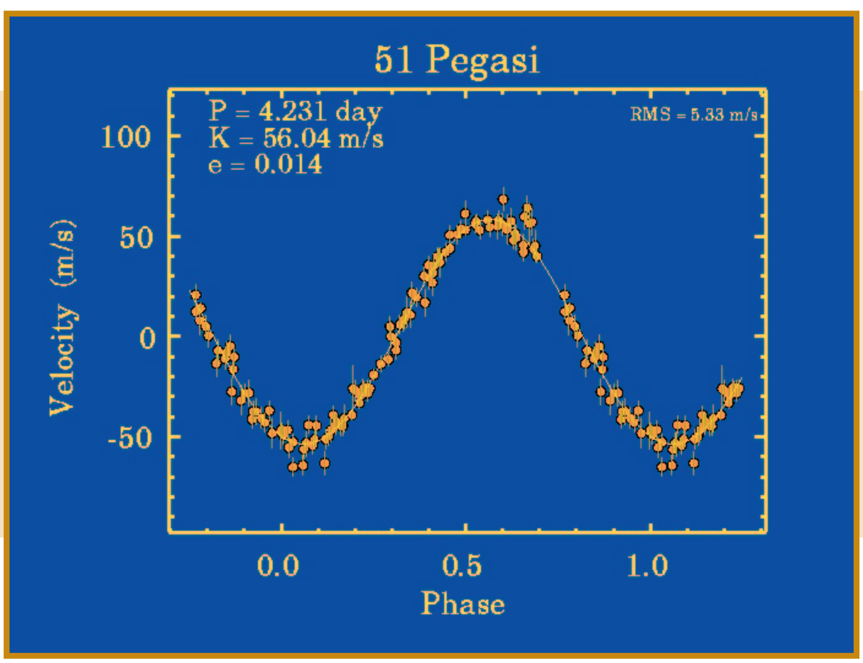
Image by John Spencer (Lowell Observatory) and NASA

have finally begun to find other planets around nearby stars, opening the door to a new era whose impact upon human history may ultmately be more significant than the discovery of the New World. The recent detection of planets around other stars is based on finding the small cyclic motions due to the gravitational pull of a companion planet. The biggest effects are produced by the most massive planets: for example, in our solar system, Jupiter (by far our largest planet, at 318 times the mass of the Earth) causes the Sun to wobble in a 12-year cycle at a speed of 13 metres per second. To detect such tiny orbital motions of other stars that might have their own Jovian-type gas-giant planets, astronomers must be able to measure stellar velocities to an accuracy of just 3 metres per second, the speed of a fast walker! Moreover, these velocity changes must be monitored over many years for their cyclic nature to reveal itself.

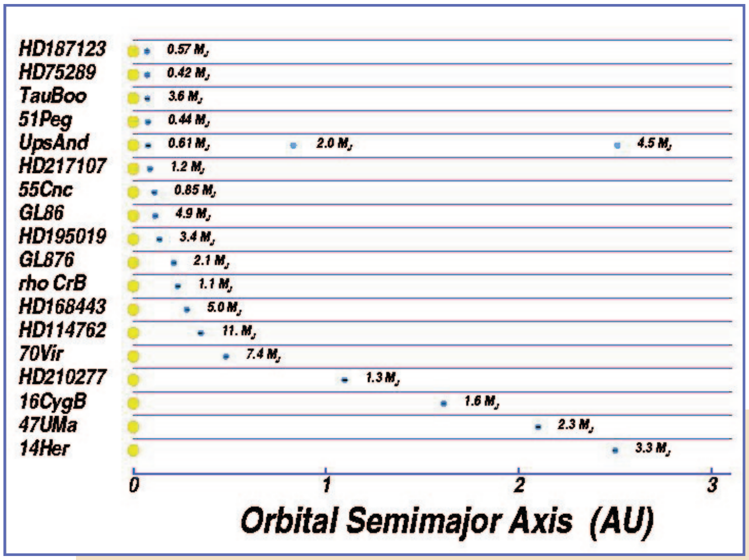
The spectroscopic techniques and instruments capable of such high precision measurements were pioneered by a Canadian team over a decade ago. Building on these techniques, several other international groups have now surveyed over 300 nearby solar-type stars; the first discoveries of Jovian-size planets around a few such stars were announced in 1995. Twenty such planets have now been found, most of them with measured masses between 0.5 and 5 times the mass of Jupiter. A major surprise about these new planets, however, is that many of them are much closer to their parent suns than the Earth is to our Sun. Most astonishing of all is the discovery this year of the first planetary system: three Jovian-mass planets have been detected to be orbiting the star Upsilon Andromedae. We now have the first concrete evidence that entire families of planets revolve around stars like our Sun!

The presence of a Jupiter-sized planet around nearby star 51 Pegasi reveals itself by the small, periodic "wobble" of the star as the planet orbits around it. Highly precise measurements of the motion of the star show that it changes by more than 100 metres per second with a period of 4.2 days.

Graph by G. Marcy and P. Butler, San Francisco State University



A host of new and compelling questions flow from these discoveries. Why are giant planets found so close to their central stars? Jupiter itself probably formed out in the gas -rich suburbs of the primordial solar system and never moved very far in or out from its place of birth. For other stars, their "Jupiters" might have migrated inwards from their birthplaces through the tidal interaction between the newly formed massive planets and the material in their surrounding, remnant protoplanetary disks. Does the fate of the much smaller terrestrial planets in one of these systems depend critically upon how common such processes might be? Planet searching will go into high gear in the coming years, and there is little doubt that, by the end of the next decade, we will have a considerably larger sample of detections to draw from. The theory of planet formation, aided by highly sophisticated computer simulations, will grow into one of the most lively subjects in astrophysics.

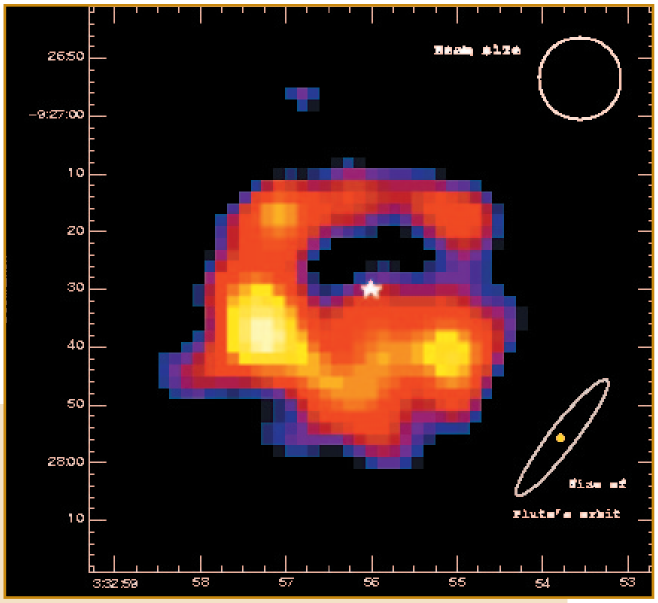


Twenty Jupiter-like planets have now been detected around nearby stars similar to our Sun by precise measurements of their reflex motions. This graph shows the estimated distance of each one from its parent star; surprisingly, most of them are much closer than 1 AU (the distance of the Earth from the Sun). Jupiter itself is 5 AU from the Sun.

Graph by G.~Marcy (San Francisco State University)

A much more ambitious goal of planetary research will be to find Earth-like – and beyond that, life-bearing — planets. This task will require entirely new instruments both on the ground and in space. Terrestrial-sized planets are the lightweights, and so exert gravitational effects upon their stars too tiny to be detected with current instruments. It may become possible to "see" them directly, by the use of still-experimental imaging techniques that block out most of the interfering light of the star itself. This will be an incredibly difficult challenge, but its fundamental importance will almost certainly drive the development of more ambitious technologies later in the 21st century. Ultimately, as the search for terrestrial planets becomes feasible, it may become possible to search for traces of carbon dioxide, water, and oxygen in their atmospheres, as signatures of biological activity.

Along with these fully formed planets, astronomers have now found examples of stars so young that they still have around them the raw material from which their planets will form. These protostellar disks of gas and dust typically extend out to 100 - 1000 AU from their central young stars (where 1 AU or "astronomical unit" is the distance from the Earth to the Sun; about 150 million kilometres). The evidence suggests that stars themselves build up by accreting gas out of these disks, while the dusty residue is used to build the planets, asteroids, and comets. Thus, planet formation and star formation processes are inseparably linked. Both take place in placental, cold dusty disks of gas, and we need to understand the physical state of these gaseous disks if we are to unravel the complete story of planetary systems. To refine this basic picture, we need to learn about the motion and chemical state of the gas and dust in



A snapshot taken in the sub-millimetre radio spectrum of a dusty disk of material around nearby star Epsilon Eridani (star at center). This image, taken with the SCUBA instrument on the JCMT, shows a diffuse ring comparable in size with our own Solar System. The ring is suggested to be a younger analog of the Kuiper Belt of protoplanetary material. The orbit size of Pluto is shown at lower right for scale.

Image from J.S.Greaves et al., Astrophysical Journal 506, L133 (1998). Reprinted with permission of J.Greaves for the authors

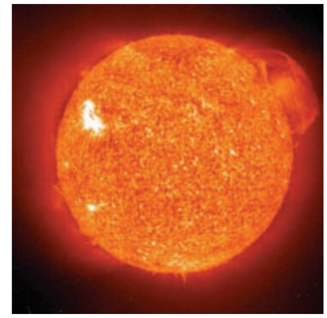
real protoplanetary disks. Where do planets form in these disks? How are the gas and dust coupled and how do they evolve chemically? Exactly how long does it take for a planet to form? Such questions can be tackled only if many more examples are studied, and at much higher spatial detail than it has yet been possible to do. The dust in protostellar disks emits radiation typically at infrared wavelengths of a few microns, while the cold molecular gas in the disk is seen at the longer millimetre wavelengths; thus two very different types of telescopes and instruments must be used to gain a complete picture of the disk structure and evolution. A few protoplanetary disks have now been detected, but even with our best current telescopes, they cannot be resolved to better than several tens of AU. Over the next decade, a major goal will be to gain views of protostellar disks at the scale of one AU or even less.

Within our own solar system, we will also learn considerably more from the actual relics of planet formation – the comets. Comets are small objects which come in from the remote outer parts of the solar system and put on a brief, spectacular show while they pass close to the Sun. Built essentially like large, dirty snowballs, they are the frozen leftover debris of planet formation and thus can potentially tell us a great deal about the early conditions of the primordial solar nebula. Comets are believed to reside in two distinct regions: the first, called the Oort Cloud, is a vast spherical region of space extending from 10,000 to 50,000 AU from the Sun. Billions of comets reside there which are believed to have been flung outward from the inner regions of the solar system at an early era by the massive Jovian planets. The second population of comets is much closer in, residing within the so-called Kuiper Belt, a zone which extends roughly from the 30 AU orbit of Neptune out to 50 AU or more. This "Trans-Neptunian" region is a topic of great current observational and theoretical interest. For example, "planets" such as Pluto and the other large Kuiper Belt objects are actually more akin to the comets in their composition and orbital properties. Canadian astronomers have contributed significantly to the search for Kuiper Belt objects and to studying the way they interact dynamically

Comet Hale-Bopp is shown here during its passage near the Sun in 1997. The dust tail (white) and ion tail (blue) are clearly separated in this photo.

Hale-Bopp photo courtesy J. Lodriguss

with the inner parts of the planetary system. Better knowledge of how comets are dislodged from their normal locations to plunge into the inner regions of the solar system is, of course, vital to understanding how frequently the Earth will undergo major, and damaging, collisions with them. The cometary collision with the Earth that may have resulted in the extinction of dinosaurs 65 million years ago, released as much energy as 10 million of the world's largest hydrogen bombs, or the equivalent of about 100 million megatons of TNT! The recent spectacular impact of the comet Shoemaker-Levy 9 with Jupiter in 1994 is a graphic reminder that such destructive impacts are still possible in our solar system.



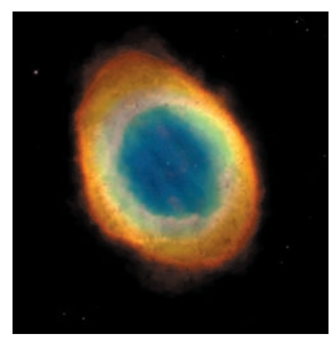
The surface of our Sun is a raging torrent of hot gas threaded by magnetic fields. This 1997 image from the SOHO satellite captured a giant eruptive prominence from the Solar surface. Energetic particles in the "solar wind" may interact with the upper atmosphere and magnetic field of the Earth, causing aurorae and even electric power disruptions.

Image from the SOHO-EIT Consortium, an ESA / NASA project of international cooperation

2.2 The Lives of the Stars

Our Sun is the nearest star. Along with the planets, it is about 4.6 billion years old, and will continue to look much the way it does now for another 5 billion years. Unique among all stars, we can study both its surface and its interior in exquisite and challenging detail. Its hot outer atmosphere is in a perpetually dynamic state as strong magnetic fields channel the hot gases along giant loops and prominences. Sometimes, the magnetic fields change abruptly and release energetic particles into space, potentially to interact with the Earth's magnetosphere and upper atmosphere in a myriad of ways. All studies of the solar atmosphere to date suggest that solar disturbances are linked to a powerful magnetic dynamo which is in turn driven by the upwelling of hot gas in the deeper layers of the Sun.

Stepping outward from our planetary system, we pass into the stellar realm. Whereas interplanetary distances are a few AU's, interstellar distances are vastly larger. They are commonly measured in parsecs, where one parsec is equal to about 200,000 AU or about three lightyears. Some stars undergo activity which is hundreds or thousands of times more powerful than that on the Sun. New arrays of radio telescopes now planned by the international community will finally allow astronomers to sample and image tens of thousands of stars comprising their full range of size and activity. At optical wavelengths, sensitive detectors and new ways to process the detected light will probe deeper into the atmospheres of both quiescent and active stars to determine their physical conditions and state of motion.



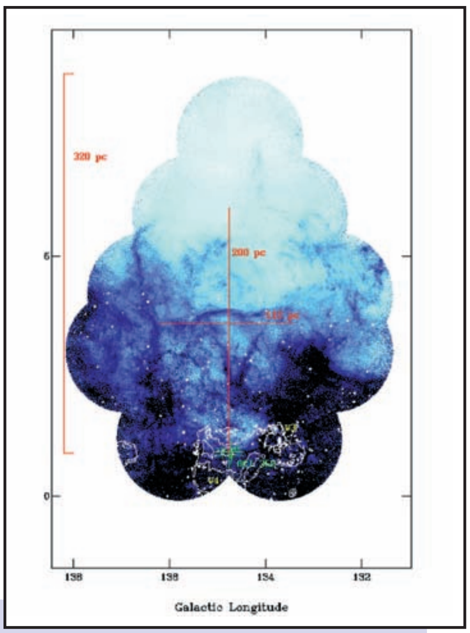
A Hubble Space Telescope view of the Ring Nebula, a shell of gas cast off by a dying star. About five billion years from now, our own Sun will experience this "planetary nebula" ejection phase. The faint, tiny star at the center of the ring will become a white dwarf star and gradually fade away.

Image by Hubble Heritage Team (AURA/STScI/NASA)

Stars are ultimately powered by nuclear fusion "reactors" that run deep in their cores. At temperatures of tens of millions of degrees and pressures that are a hundred billion times greater than that exerted by the Earth's atmosphere upon us, the lighter atomic nuclei at the centre of our Sun, principally hydrogen and helium, are fused into heavier ones. This liberates tremendous amounts of energy. All the other elements found in nature, such as carbon, oxygen, silicon, and iron, are built up this way in successive generations of stars. Nature's most elusive known particles, the neutrinos, are also released as a by-product of these fusion reactions. The panorama of stellar evolution, that encompasses how a star burns its nuclear fuel to exhaustion and then either dies away quietly or explodes violently, represents one of the most well developed fields of astrophysics. This subject requires the input from many areas of physics, as well as the use of sophisticated, numerical techniques and modern, high-speed computers.

Our theories and models of stellar structure will be tested during the coming decades to a level almost unimaginable 15 years ago. Although the Sun's deep interior cannot be directly seen, the rates of nuclear reactions there can be directly measured by detecting the flux of all types of neutrinos that travel to us from the Sun's center. The measured flux of one type of neutrino is a factor of two smaller than predicted by our best computer models of the Sun. The solution to this well-known puzzle may lie in the ability of the neutrinos to change their type. New international neutrino observatories, including the Sudbury Neutrino Observatory (SNO) with its unique detector consisting of 1 kiloton of Canada's reserve of heavy water, as well as the Super Kamiokande observatory in Japan with its 22 kilotons of ordinary water, have been designed to resolve this problem. They will thereby make critically important contributions to both astrophysics and particle physics.

A second remarkable way of deducing the interior conditions within stars is through the new technique of stellar seismology – in essence, by analyzing how stars vibrate. In the same way that geologists can use the aftershocks and tremors from earthquakes to deduce the interior structure of the Earth, the way that the Sun "rings" in response to the disturbances created by its own boisterous inner convective motions can tell us a great deal about its internal structure. Astronomers measure the tiny stellar oscillations using highly sophisticated spectroscopic observations from ground-based optical telescopes, and increasingly, from space-based observatories. The coming decades will allow us to extend these studies to other stars of very different sizes, masses, and evolutionary states.

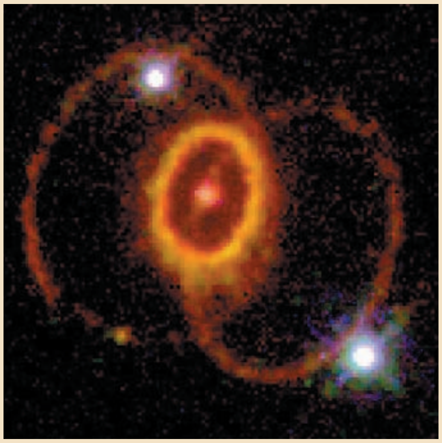


A composite image generated by the Canadian Galactic Plane Survey at DRAO. Here a vast swath of the northern plane of the Milky Way is seen at radio wavelengths, showing formation of a "chimney" in the interstellar medium as a consequence of ionizing radiation, and winds from massive young stars in the W4 region of the galaxy.

Image courtesy Russ Taylor (University of Calgary) and DRAO / HIA

The evolution and fate of a star depends upon its mass and composition. The smallest stars that can become hot enough in their interiors to ignite nuclear fusion are about 0.08 times the mass of the Sun, while the biggest known are nearly 100 times the Sun's mass. The low-mass stars live many billions of years, die out rather quietly, and do very little to their surroundings. High-mass stars, by contrast, live short but extravagant lives as they burn their fuel at prodigious rates for only a few million years before finally exploding as supernovae. These supernovae inject huge amounts of energy back into the gaseous interstellar medium, along with the heavy-element products of the nuclear fusion chain. Thus the massive stars, although they are small in number compared with the low-mass ones, are the ones which drive the grand cycle of stellar history in our Galaxy, the Milky Way. From interstellar gas clouds, stars are born and begin their active nuclear burning lifetimes; they evolve, eject their processed material back into space, and the material mixes with other interstellar gas to create a new generation of stars. The powerful outflows of gas from massive stars also exert strong effects on the heating of the interstellar gas and the rate at which it can form new stars. It is also no exaggeration to say that all living things upon the Earth, and probably other planets, are the children of the stars. The elements heavier than hydrogen and helium, out of which we are made, were created in the interiors of earlier stars.

The supernova explosion, which is the endpoint for stars more massive than about 8 times the mass of the Sun, is the most spectacular stellar phenomenon. For a brief period of days or weeks, the expanding supernova shell can be brighter than the combined light from billions of normal stars, making it a beacon bright enough to be seen even in a remote galaxy. The famous supernova SN1987A, first discovered by a Canadian astronomer, was the visible result of the destruction of a 15-Solar-mass star in our nearby dwarf companion galaxy, the Large Magellanic Cloud. It has been the most closely studied supernova in history and has played a crucial role in allowing astrophysicists to compare the predictions of models with the real thing. A particularly important result was the confirmation that the supernova detonation event, which is set off by the sudden collapse of the dense core of the star, should release a huge flux of energetic neutrinos. Neutrino bursts were received from SN1987A at detectors in Japan and the USA just before the optical light wave arrived. The next comparable supernova explosion in our galaxy, or its neighbours, will be readily detected by their successors at SNO and Super-Kamiokande.

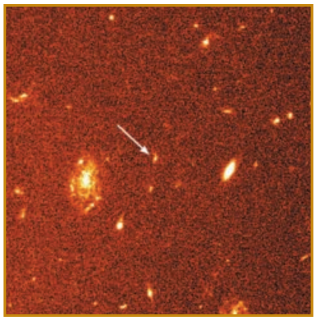


This striking HST image of supernova SN1987A in the Large Magellanic Cloud shows bright rings of glowing gas many light-years across, encircling the site of the explosion.

Image by Christopher Burrows (ESA/STScI) and NASA

A central neutron star or black hole may be left behind as the dead remnant of the original star's core. A neutron star has a mass similar to that of the Sun, yet may be no more than 20 km in radius. Such an object can be denser than even the nucleus of an atom, and a full understanding of such a compressed state of matter is still being explored. But it is the black hole which represents the ultimate condition of collapsed matter. If the entire core of the star collapses to within a critical radius (equal to about 3 kilometers for one solar mass of material), it becomes completely sealed off to outside view: not even light can escape from it, and outside material such as gas from neighboring stars can be swallowed up in it but cannot come back out. Nothing can prevent such a collapsing star from reaching a state known as a singularity at its centre. Such an entity is governed by both quantum mechanics and general relativity for which there is, as yet, no unified physical theory. By carefully measuring the orbital motions of stars in binary star systems that appear to have massive, but unseen companions, astronomers now have superb evidence for the existence of at least 8 stellar mass black holes in our galaxy. What appeared to physicists 70 years ago to be an inconceivable consequence of Einstein's general theory of relativity, has in the late 1990's become a near certainty; black holes exist. We will surely need to know how common they are in the Galaxy and to learn how they are formed.

Neutron stars may also represent the key to understanding the remarkable phenomenon of gamma-ray bursts that have been observed by satellites since the early 1970's. These are short-lived bursts of extremely high energy radiation, visible only from satellite gamma-ray detectors, but which occur everywhere around



The most energetic events generated in space may be the enigmatic "gamma-ray bursters" which explode suddenly and fade away within days. The Hubble Telescope captured this image of the extremely faint, distant galaxy (arrow at center) which is the host galaxy of a gamma-ray burst.

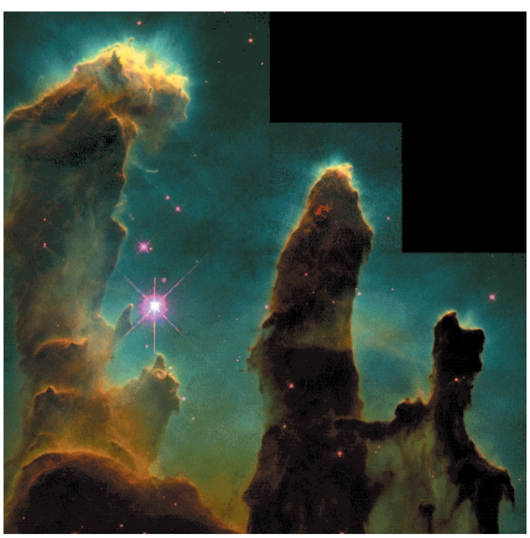
Image by S.R.Kulkarni and S.G.Djorgovski (Caltech), the Caltech GRB Team, and NASA

the sky. Very recently, the “afterglow” from a few of these bursts has been seen at longer wavelengths (X-ray, optical, and radio), and the evidence now suggests that these are occurring in galaxies at “cosmological” distances in the early universe. The huge amounts of energy that pour out of such bursts could be released during the rare collision and merger of two neutron stars, with the end result being a black hole. The potential exists to use these unique objects, not just to investigate stellar collapse to a black hole, but to probe conditions within galaxies at much earlier times.

2.3 Star Formation

How do stars actually form? Once a star has emerged from the raw material of the interstellar medium, we can predict in impressive detail how it will evolve and end. But its very first stage is still poorly understood: it is an extremely challenging problem on both observational and theoretical grounds, and a fully detailed theory of star formation has not yet been constructed. Yet it is crucial to further progress in understanding the complete history of the Galaxy. Star formation sets the stage for the process of planetary formation, and the feedback between actively forming stars and their large-scale surroundings, through stellar winds and supernovae, affects the formation and evolution of an entire galaxy. No true progress can be made in any of these fields without a deep understanding of how star formation occurs, here and now.

A particularly important observed quantity that a successful theory must explain is called the Initial Mass Function (IMF), which is the relative number of stars formed at a given mass. The IMF prescribes the numbers of high-mass stars (and thus the rate at which the composition of the Galaxy’s raw material can cycle through supernovae), as well as the numbers of the so-called “brown dwarfs” – stars whose mass falls below the 0.08-Solar-mass limit for hydrogen fusion. Brown dwarfs are ultra-faint, making them exceedingly hard to detect; but if large numbers of them exist, they could make up a significant fraction of the ubiquitous “dark matter” that dominates the mass of the galaxies. The new generations of optical and infrared telescopes, such as Gemini and NGST, will play major roles in the search for brown dwarfs and the study of star-forming nebulae all over the Milky Way.



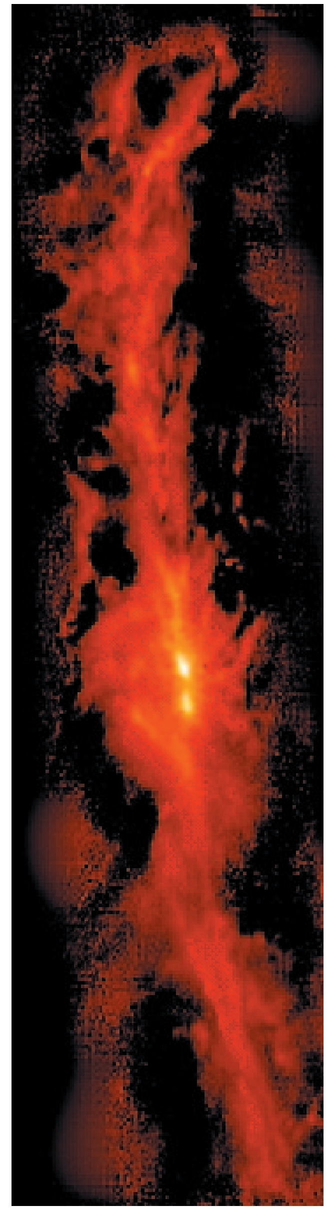
These "pillars" of gas in the Eagle Nebula, viewed with HST, show dense clouds of molecular hydrogen and small globules where embryonic stars may be located.

Image by Jeff Hester and Paul Scowen (Arizona State University) and NASA.

Active star formation takes place in the disk of our own Milky Way Galaxy inside special types of dense nebulae called molecular clouds. These clouds were discovered serendipitously in the mid 1960’s, by astronomers using radio telescopes tuned to the millimeter wavelengths at which many kinds of molecules in space emit radiation. A molecular cloud in the Milky Way may contain up to several million solar masses in cold gas, over a region of space tens of parsecs across. The temperatures within these clouds are normally 10 - 20 degrees above absolute zero (or about minus 250 degrees Celsius) and the gas is mostly in the form of hydrogen molecules, with trace amounts of more easily detected material such as carbon monoxide (CO). It is primarily the millimetre-wavelength emission of CO molecules that allows us to map and study these clouds. Astronomers have, in the last few years, mapped molecular clouds in other nearby galaxies and have even found CO emission from galaxies that are only a few billion years old!

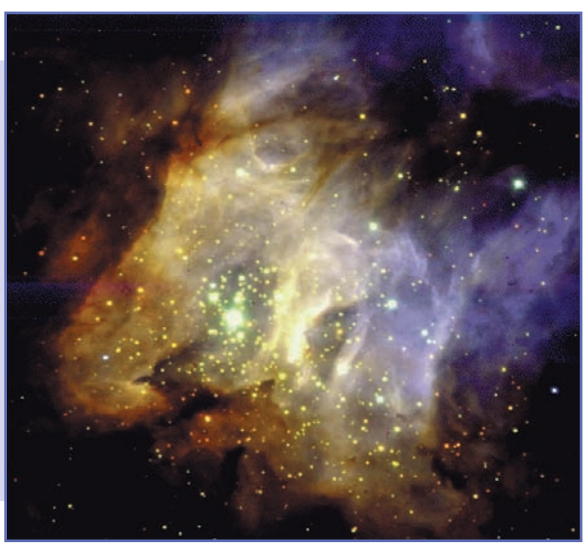
The new tools for observing at infrared and millimetre wavelengths that began to be developed over the last 20 years have revolutionized the observations of star forming regions. The optical light from stars still embedded in their natal molecular clouds is blocked because it is absorbed by dust that is mixed in with the cool, dense, molecular gas. However, infrared light from young stars and heated dust, as well as the millimetre radiation from gas molecules, can propagate almost unhindered out of these dense dusty realms. The enormous amount that we will learn about star formation in greater detail provide one of the strongest motivations for investing in the more advanced infrared and millimetre telescopes that will come on line in the next decade.

Molecular clouds would quickly undergo gravitational collapse without some means of internally supporting their huge weight. They are too cold to be supported simply by the internal pressure of hot gas, as stars are; instead, they rely upon the pressure that is provided by the magnetic fields that are woven through them. The actual conversion of clumps of gas into stars takes place within smaller, high pressure regions known as molecular cloud cores. New, high-detail infrared images of molecular cloud cores also make it clear that stars seldom form in isolation, but emerge as members of stellar groups and clusters. Star formation is a highly gregarious process, for reasons that still need to be discovered.



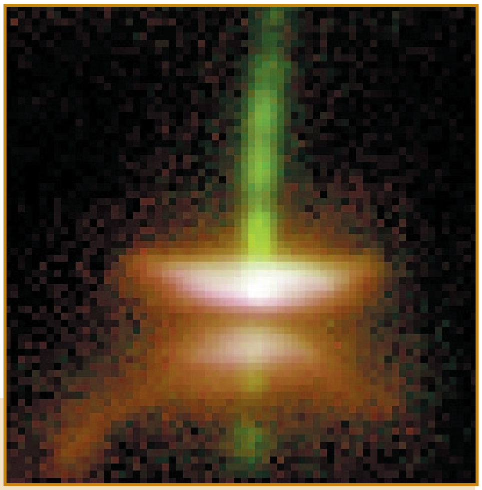
A "ridge" of molecular gas many light years long within the Orion nebula, as seen at a wavelength of 450 microns. Two bright knots near the center indicate the densest parts of the ridge where individual stars are beginning to form. This image is taken with the SCUBA instrument on the JCMT telescope.

Courtesy Dr. Doug Johnstone, CITA



Many regions within our Milky Way galaxy can be found where dense amounts of gas and dust have collected together. These nebulae are the sites of new star formation. In this nebula, called RCW38, a cluster of stars at the center is lighting up the surrounding filaments of gas and dust from which it formed.

Image from Very Large Telescope (VLT) at the European Southern Observatory (ESO), Chile. Copyright ESO



One of the first direct photographs of a protostellar disk around another star. A young star called Herbig-Haro 30, surrounded by a thin dark disk, is seen ejecting gaseous jets away from the plane of the disk. The new telescopes to be deployed in the next decade will reveal these dimly seen young stars in vastly greater detail.

Image by Chris Burrows (STScI), the WFPCZ Science Team, and NASA

Finally, individual stars within such clusters may form through the gravitational collapse of individual molecular cloud cores; regions of gas much less than a parsec in size. As a slowly rotating core collapses inward, it rotates ever more rapidly to conserve the total amount of "spin" (angular momentum) held by the original extended cloud. Exactly the same type of process occurs as spinning figure skaters pull in their arms in order to spin even faster. The increasing spin of the collapsing gas prevents it from reaching the central protostar directly; instead it forms a rotating disk. Astronomers are making a concerted effort to detect such collapse motions, and to observe the process of disk formation and evolution. Such research programs require the extremely powerful millimetre wave and infrared telescopes that are being planned for the coming decade.

One of the most spectacular and beautiful aspects of star formation is the pervasive appearance of violent outflows and jets from the vicinity of young stellar objects. No theory anticipated the discovery, in 1980, of highly energetic molecular outflows that accompany the birth of all stars. An outflow is now recognized to consist of gas that is swept up by the pressure of an underlying, highly collimated jet. While most molecular outflows move at tens of kilometres per second, jets have speeds in the range 200 – 400 kilometres per second and may be several parsecs long. Jets and outflows carry off much of the energy and angular momentum that is released as the accretion disk spirals into the central protostar. Outflows and jets are closely linked with the presence of accretion disks around young stars. They are also among the first visible sign-posts of the star formation. Sorting out the currently contending theories for the way the jets are created and how they are linked to the formation of stars is a major challenge that will require high-detail observations at optical, infrared, and millimetre wavelengths, capable of probing to within an AU of the central protostar. Investigating the characteristics of accretion disks, jets, outflows, and the entire sequence of steps in star formation will provide one of the major scientific themes of our Long Range Plan for the next decade.

2.4 Galaxy Formation and Evolution

The outward step from stars within our own Galaxy, to the realm of the galaxies themselves, is a huge one. Distances between these immense "cities of stars" are measured typically in millions of parsecs, between which are unimaginably vast stretches of nearly empty space. The Milky Way is a collection of perhaps a hundred billion stars along with several billion solar masses worth of interstellar gas, all held together by their mutual gravity. Galaxies are the great arenas in which stars, planets, and life itself play out their history.

Some galaxies are much larger than the Milky Way; but most are much smaller. Galaxies vary considerably in their mass and take on several different forms; from the small “irregulars” that have quite chaotic and unorganized structures and contain lots of gas, to the “disk galaxies” with their elegant spiral arms rotating like majestic pinwheels around a bright nucleus, to the “ellipticals” that are structurally simple, enormous collections of stars. In the first few decades of the 20th century, it was commonly thought that large galaxies were “island universes” living passively in ever growing isolation as they are carried farther apart by the cosmic expansion. Today, little is left of that simple picture. Most galaxies are found gathered together in groups and clusters; the sparsest of these may contain as few as half a dozen individual galaxies, while the largest hold thousands. Galaxy clusters and superclusters define vast filaments and sheets spanning hundreds of millions of parsecs that are separated by even larger voids. How did this proliferation of structure arise? What characteristics of their raw gaseous material and dark matter control the form of galaxies at any time and their distribution in space?

This elegant pinwheel form is the spiral galaxy NGC1232, in the southern sky. Our own Milky Way galaxy may look like this, with bright, young stars and gas clouds lining up along the spiral arm segments.

Image from Very Large Telescope (VLT) at the European Southern Observatory (ESO), Chile. Copyright ESO

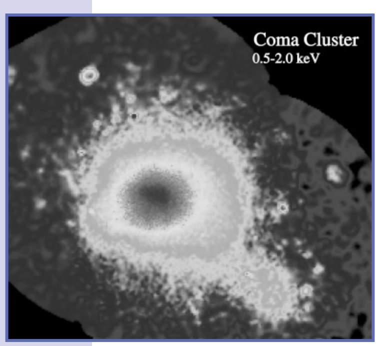
Galaxies as a whole should be viewed as dynamic entities whose masses, gas content, and stellar populations evolve with time. Small galaxies that are gas-rich can completely transform their appearance during sporadic “starbursts” in which much of the gas condenses quickly into stars. The huge numbers of supernova explosions that accompany such bursts are sufficient to blow much of the remaining gas out of these tiny galaxies and scatter their heavy elements into the highly diffuse, intergalactic medium in which galaxies themselves are immersed. Larger galaxies such as the Milky Way can grow by accretion, as occasional small satellite galaxies fall into them. The largest galaxies of all, the giant ellipticals at the centres of large clusters of galaxies, have been found by satellite X-ray imaging to be surrounded by huge, tenuous halos of gas heated to millions of degrees; the total amount of mass in this gas in some cases adds up to considerably more than the mass in all the stars of all the galaxies in the cluster.

The Large Magellanic Cloud, a satellite of our own Milky Way, is about 160,000 light years away but is easily visible to the naked eye in the night sky of the southern hemisphere. Patches of active star formation (light red) are scattered all over the older main body of this small galaxy.

Photograph from UK Schmidt Plates by David Malin. Copyright Royal Observatory, Edinburgh and Anglo-Australian Observatory

In large groups of galaxies, the "intracluster space" between the galaxies is often filled with hot gas that is detectable at X-ray wavelengths. This hot, tenuous material can exceed the mass in all the individual galaxies, and may represent gas left over from the early formation stages, mixed in with some ejected from within the galaxies by supernova explosions. This ROSAT X-ray picture of the Coma cluster of galaxies shows a vast, 6 million light year wide cloud of this high-temperature gas.

Image by Dr. S. L. Snowden, obtained with the ROSAT satellite (NASA/GSFC)



This galaxy, NGC 4594, is commonly called the Sombrero. With its huge central nucleus and only a small, dusty disk circling around it, it is built almost entirely of old stars.

CFHT Corporation. Image courtesy Jean-Charles Cuillandre, CFHT

Much of the gas may be unused material left over from the early cosmos, while some of it is material ejected from within the galaxies by supernovae.

Many large galaxies have supermassive black holes at their centres that are from millions to billions of times more massive than the Sun. Astronomers can measure the masses of these "monsters" in the hearts of galaxies by studying the orbital motions of luminous, radio-emitting, blobs of gas as well as those of luminous massive stars, around the centres of galactic nuclei. The presence of supermassive holes may be the only viable way of explaining the energy liberated at the centres of super-active galaxies. The nuclei of these galaxies generate up to 100,000 times more energy than the total liberated by all of their stars, in a region that is much smaller than a parsec in size (such a region can easily accommodate even a billion solar mass black hole, which is only 20 AU in size). The engine that is almost certainly responsible for this copious output involves the accretion of gas through a disk that orbits a monster black hole. The efficiency of such an accretion process onto a central rotating black hole rivals that of nuclear reactions, making the accretion of gas onto black holes nature's most efficient form of energy conversion. By feeding massive black holes with sufficient gas (about a mass of our Sun per year in the most extreme cases), the nuclei of galaxies are transformed into the active high-energy states called Seyfert galaxies or even quasars, the most luminous types of galaxies. The universe currently harbours relatively few quasars in comparison with the large numbers of quasars that were active billions of years ago as galaxies were being assembled. This is another sign that galaxies evolve significantly with time and that the monsters lurking at their centres are now being relatively starved for gas.

A disk of gas and dust 800 light years across swirls around a giant black hole deep in the center of galaxy NGC 4261. This optical image is from the HST.

Image from H. Ford and L. Ferrarese (Johns Hopkins University) and NASA.

One of the greatest adventures of astrophysics over the next two decades will be to understand the long-vanished first epoch of galaxy formation. It is almost certain that the most active epoch of galaxy formation happened in the first 20 percent (3 billion years) of the universe's history and that the present-day level of activity, fascinating though it is, can be only a shadow of its former self. How do we gain direct evidence of this — that is, how do we catch galaxies in the act of formation?

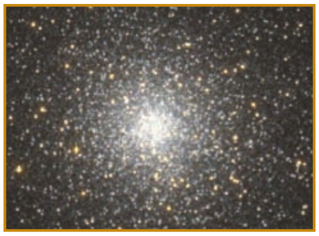
The direct route is to take advantage of the finite speed of light. The farther away that a galaxy is, the longer it has taken for its light to reach us. Thus, we view it as it was, eons ago. This "lookback time" gives us, in essence, a time-machine that allows us to view faint, distant galaxies as they were only a few billion years after the Big Bang. The new tools deployed during the past decade, such as the Hubble Space Telescope (HST) and the giant 8 metre class telescopes on the ground, have just started to give us the ability to bring such remote targets within reach. These extraordinary new observations are beginning to show that the further back in time we look, the patchier the distribution of galaxies seems to become. The scene at these early times is dominated more and more by smaller , more gaseous pieces, rather than a few large, fully formed galaxies of stars.

These results, preliminary though they are, give considerable support to theoretical interpretations which predict that galaxies build up by a "bottom-up" process wherein small systems merge to form larger ones. As we look even further back to a time before galaxies had converted their gas into stars, we must also employ radio telescopes that allow us to make high resolution studies of the state of protogalactic gas. The new generations of world observatories will play pivotal roles in these studies.

The Hubble Telescope has supplied us with the deepest look into the universe of galaxies in space. This ultra-long-exposure image of a tiny part of the northern-hemisphere sky, now called the "Hubble Deep Field", reveals a myriad of faint, remote galaxies. Most of these are seen as they were when the Universe was only half as old as it is now.

Image by R.Williams and the Hubble Deep Field Team (STScI / NASA)

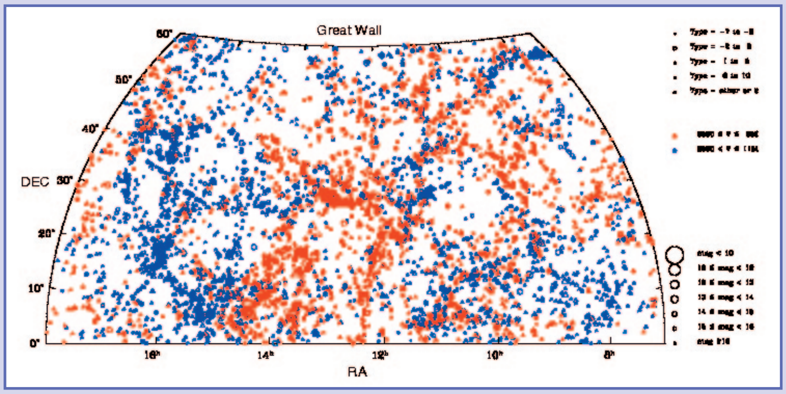
A complementary approach is to deduce the histories of galaxies through our increasing ability to resolve and study the individual stars within other galaxies. The new telescopes on the ground and in space now allow us to see relatively nearby galaxies (ones only a few million parsecs away) in considerable detail — star-forming gas clouds, clusters of stars, and even the individual stars themselves. The advantage of studying nearby galaxies is that their constituents can be measured in immensely more detail than cosmologically remote objects. In a remarkably direct sense, what we do by probing the makeup of nearby galaxies resembles archaeology on a cosmic scale; the "layers" of stars formed at different times within the galaxy can be either simple or complex depending on their individual histories. The very oldest parts of these galaxies, and the objects most interesting for cosmology, are the globular star clusters that are tightly clustered groups of thousands of old stars (their study has long been a Canadian specialty). The ages of the globular clusters are in the range from 12 to 14 billion years, according to the best combinations of stellar evolution theory and observational data that we have at present. Because these ancient objects are present in every large galaxy, they provide what seems to be a common thread in the story of galaxy formation, and give us a key link between stellar astrophysics and cosmology.



The central part of the globular star cluster NGC 6356, an ancient cluster of stars within our own Galaxy.

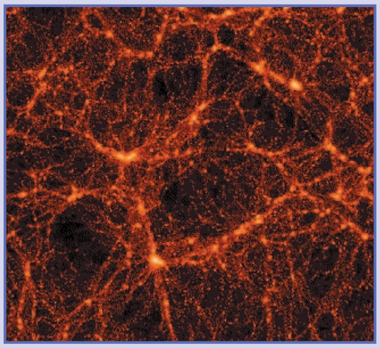
Courtesy J.-C. Cuillandre, CFHT

Galaxies formed in the early universe by transforming their raw material — the hydrogen and helium gas emerging from the Big Bang, along with the ubiquitous, non-luminous "dark matter" — into the forms we observe today. Thus an understanding of galaxy formation flows seamlessly from some of the basic ideas of cosmology. The current large-scale picture that we have of galaxy formation is that the original, tiny ripples in the density of matter that emerged out of the Big Bang (see below) should grow with time. Eventually, these regions become dense enough to become distinct entities that separate out of the general expansion. The gas that collected into the resulting dark matter "wells" cooled to form the clouds that were probably the nurseries for the first stars that were born in our Universe. The radiation from these first stellar objects lit up the Universe as galaxies began to assemble and grow. Theoretical modeling has advanced stride for stride with the new observations, and will continue to do so as it is driven onward by computing technology. N-body simulations involving millions and even billions of simulated "particles" will acquire



This graph shows a slice of our local universe, a region of space about 650 million light years across. Each dot represents one galaxy, with red and blue patterns showing two parallel "layers". The galaxies are distributed in great strings and filaments stretching millions of light years across space.

Graph courtesy John Huchra and Margaret Geller (Harvard Smithsonian Center for Astrophysics)



This computer model shows what a section of the early universe might have looked like at the time when galaxies were beginning to form, about one billion years after the Big Bang. Here the primordial gaseous material has already begun to gather together into lumps and filaments, which will grow with time into full-scale galaxies.

Computer model image courtesy Hugh Couchman (McMaster University)

the rich data that the next decade's complementary observatories will be amassing. Realistic simulations must include dark matter, stars, and gas. An essential point brought home by these numerical experiments is that the dynamic range of the formation process is enormous: it involves the clustering of the gas and dark matter on all scales from molecular clouds within the protogalaxies up to whole groups and superclusters of galaxies on scales a million times larger. Galaxy formation is, therefore, at once a local and a global process, and our theoretical and computational techniques will need to become ever more sophisticated in order to deal with this.

2.5 Cosmology

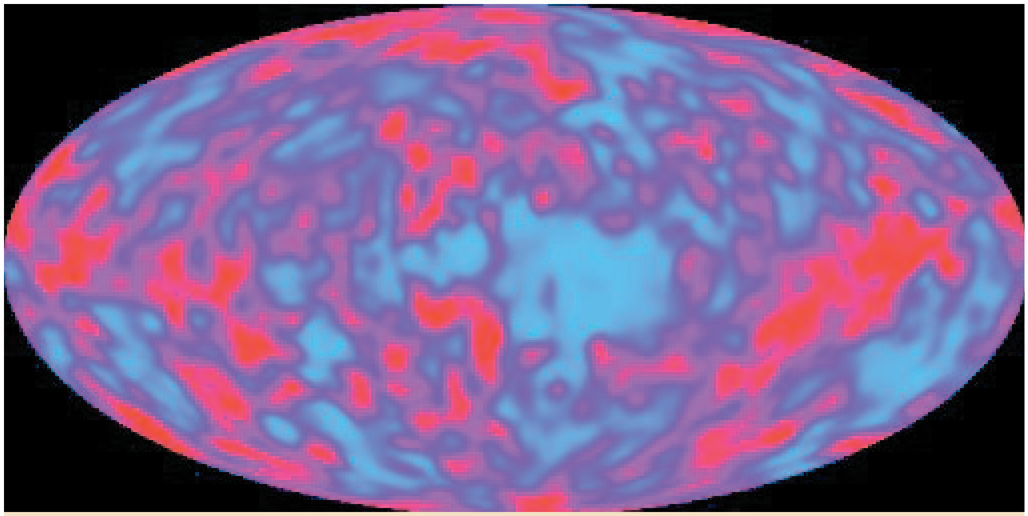
Humans have always wondered: What is the universe made of? How did it begin, and how will it end? These questions are simple, yet profound. Our current understanding of the structure of the universe on its ultimate large scales follows from the remarkable theory of general relativity, published by Albert Einstein in 1915. It sets out a view of gravity and space that has since become one of the most exhaustively tested theories in all of physics. Its basic tenet is that matter curves the very structure of space and time, much the way that a ball lying on a taut rubber membrane stretches its surface. At the same time, curved space tells an object how to move as it travels through the curves and valleys.

On the very largest scales that we can observe, now up to billions of parsecs, galaxies and clusters of galaxies appear to be uniformly spread throughout the universe. Einstein showed that a universe containing such a homogenous distribution of matter cannot simply be static; it must either expand or contract with time. In the 1920's, Vesto Slipher and Edwin Hubble used measurements of the distances and motions of galaxies around us to reveal that, in fact, the galaxies recede from each other: they had discovered the expansion of the Universe, now called Hubble's Law. The rate of expansion that is deduced from this – the average velocity of the galaxy divided by its distance — is known as the Hubble constant, H_o. This concept can be visualized by imagining galaxies to be like raisins embedded in a loaf of baking bread. As the dough rises, it carries each raisin increasingly farther away from every other raisin. Just like the dough in this example, it is the expansion of space-time itself that carries galaxies increasingly farther apart from one another.

An immediate consequence of Hubble's Law is that the size of the universe changes with time. It must have been much more "compact" in the past, originating in a "Big Bang". Huge efforts have gone into measuring the value of the Hubble constant H_o because, according to the simplest form of the Big Bang model, it gives us a measure of the age of the universe. Current measurements of H_o translate into an "expansion age" of 10 to 13 billion years for standard cosmological models. Depending upon the exact value, there could be a major outstanding problem in reconciling the age of the universe and the ages of its oldest stellar systems, the globular clusters. If the universe is undergoing accelerated expansion, then the best current models suggest that it could be 15 billion years old.

Two other consequences of the Big Bang model have been beautifully confirmed. Just as hot gas cools when it expands, so too does the universe. The expected fossil radiation from the era before the galaxies existed, when the universe was nothing but a mixture of dark matter and hot, dense, and opaque gas, was detected in 1965. This is the Cosmic Microwave Background Radiation (CMBR) that fills all of space, the visible relic of this long-vanished early epoch. It was emitted when the universe was cool enough to become transparent to this radiation and for the radiation to decouple from the matter; when it was less than a million years old. Today, the CMBR appears as cold microwave radiation whose temperature is just 2.735 degrees above absolute zero. The tiny ripples in it (no larger than a few parts per million) detected by the COBE satellite mission a decade ago may represent the seeds of regions where clusters of galaxies would eventually grow. Astronomers are making concerted efforts both in ground and space-based observatories to measure these tiny fluctuations down to much smaller angular scales, because these contain the direct record of how structures such as the galaxies evolved from a nearly smooth pre-galactic universe. The coming decade will see the launch of several important new missions whose task will be to map this microwave background radiation on much finer scales than COBE achieved.

A third triumph of the Big Bang picture came from the realization, half a century ago, that there must have been a time in the early universe when the material was hot and dense enough to resemble the interior of a star. During this



An all-sky map of the Cosmic Microwave Background, the residual glow of the Big Bang. The colour differences shown correspond to tiny ripples in the temperature of this radiation filling the entire sky, amounting to differences of less than 1 part in 100,000.

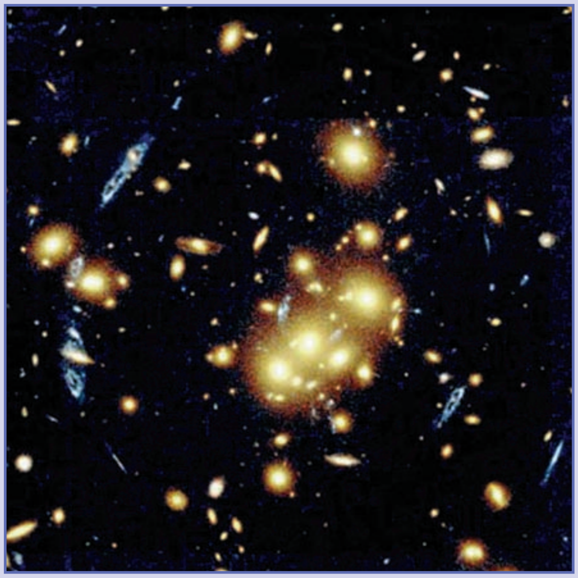
Courtesy NASA / GSFC

brief epoch, nuclear fusion reactions would have occurred, starting with the basic subatomic particles (neutrons and protons) that were present then. This era of element production happened when the universe was less than three minutes old and had cooled to a temperature of a billion degrees. The ongoing expansion quickly cooled the gas below the point where fusion could continue, but the end result of this brief phase of nucleosynthesis turned the material into a mixture of very simple elements: primarily hydrogen, some helium, and trace amounts of lithium and deuterium. The detailed calculations from the model are found to correspond superbly with the proportions of these elements that are found in stars. Thus the light elements in today's universe are the remnants of the Big Bang; all the heavier ones are the later result of nuclear fusion within the stars themselves.

But despite the resounding successes of the standard Big Bang model, a number of major unresolved issues remain. Whether or not the universe will continue to expand forever must still be determined. The answer depends in part upon making good measurements of the average density of matter in cosmological space. According to general relativity, the geometry (overall curvature) of the universe depends upon this average mass density: if it is too low, the mutual gravitational attraction of all the galaxies and dark matter will be too weak to bring the eternal expansion to a halt. If the density is, however, higher than a certain threshold value, then the universe will expand to a maximum size and then recollapse to a "Big Crunch". The ratio of the average density of all kinds of matter in the universe to this threshold value is called Ω_0; if Ω_0 is less than 1, then the universe will expand forever.

Many of the major observational programs in cosmology are designed with the goal of measuring this elusive density ratio. Since dark matter makes up most of the mass of the universe, astronomers have devised sophisticated techniques to measure both its luminous and dark matter content. The presence of dark matter is determined by its gravitational influence upon luminous matter. Thus, the orbits of stars within disk galaxies are largely determined by the distribution of dark matter within them. The same can be said about the motions of galaxies within rich galactic clusters. Finally, astronomers can also map out the distribution of dark matter in galaxies and clusters of galaxies by looking at their ‘gravitational lensing’ of yet more distant objects. This important technique is based upon the prediction of Einstein’s theory of general relativity that light, too, follows a curved path as it nears and passes concentrations of matter. This wide variety of observations, some performed by Canadian groups using the Canada-France-Hawaii telescope, tend to give a value of Ω_0 of at most 0.3, well below the threshold density. However, this result does not explain another major fact, namely, the observed smoothness of the CMBR radiation across the sky.

In the standard Big Bang model, different regions of the universe could have begun expanding at different moments and therefore would have very different temperatures today. Somehow the universe must have been homogenized at early times. While the standard picture outlined above has no explanation for this, a new model developed in the 1980’s called “inflationary cosmology” does. In this picture, our visible universe originated from a finite region which, when it was much less than the size of a proton, underwent an era of tremendously rapid (inflationary!) expansion in its first, unimaginably small, fraction of a second. This initially tiny region subsequently settled into the normal expansion state described by the standard Big Bang model. Though this approach explains the smoothness of the CMBR, it also predicts that the density ratio Ω_0 should be almost exactly 1.0, which is at odds with many of the current painstakingly accumulated measurements discussed above.



This distant, rich cluster of galaxies contains a huge amount of mass which acts as a "gravitational lens" for light from even more distant objects behind it. The blue arcs are multiple distorted images of the same distant galaxy, whose light has passed through the huge gravitational field of the cluster.

Image by W.N.Colley and E.Turner (Princeton University), J.A.Tyson (Bell Labs, Lucent Technologies) and NASA

A new breakthrough in observational cosmology that has the potential to address these puzzling difficulties is the putative discovery that the universe may actually be accelerating its rate of expansion. The surprising faintness of supernovae in very distant galaxies suggests that they are actually farther away than the standard model of the Hubble expansion would predict, which implies perhaps that the expansion rate of the Universe is accelerating. This could be driven by the “vacuum energy” that Einstein introduced into his general relativity equations, though he later considered it his “greatest mistake” after Hubble’s discovery of the expansion. This “cosmological constant” measures the amount of the putative vacuum energy density in space. The coming decades will see concerted efforts by astronomers to survey the universe even more deeply to test this most remarkable idea.

On the threshold of a new century, modern astronomy and astrophysics are poised to attack many of the most challenging and profound questions in all of science. The scientific goals of elucidating the origins of planets, to those of stars and galaxies, and outwards to the very structure of the universe itself, will require the construction of a series of complementary new observatories that will project far beyond the capabilities of our current facilities and require the development of many new technologies. We turn next to survey the achievements and capabilities of Canada's current complement of observatories and their role in the coming years.

CHAPTER 3

Astronomy and Astrophysics in Canada Today

Modern astronomy is a truly international venture and Canadians have played outstanding and well defined roles in its development. In 1999, Canadian astronomers represent a numerically small, but scientifically highly respected community on the world stage. Our impact upon the design, science, and technology of the twin Gemini 8 metre, the CFHT 3.6 metre, and the JCMT 15 metre telescopes; our leadership in such important collaborative projects such as the Canadian Network of Cosmology (CNOC), the Canada-France Redshift Survey (CFRS), the Canadian Galactic Plane Survey (CGPS), and the CADC's archiving of HST and other crucial data sets; as well as our prominence in theoretical astrophysics that flows from CITA's presence, are just a few examples of an impressive, internationally recognized, record of innovation and accomplishment over the last three decades.

At the same time, we must emphasize that Canadian astronomy currently lacks several major strategic capabilities that our partner nations enjoy. In comparison with our counterparts in other industrialized nations, Canadian astronomers in 1999 have little access to space based observatories, few means with which to train instrument builders and produce small instruments for the future observatories, and suffer funding levels that are anomalously low and completely insufficient to enable our participaton in the new world-scale observatories that will dominate the coming decades of astronomy.

In this chapter, we take a comprehensive look at the current Canadian astronomy research community: the range of facilities that it employs, the impact that its people have made in using them, and its success in training new generations of skilled technical people and scientists.

3.1 International Observatories

Canadians participate in international observatories that are located at some of the highest-quality sites in the world. Observing time at these premier facilities is obtained through regular competitive applications by the astronomers within each partnership. In most cases the oversubscription factor (number of nights requested each semester, divided by the number of actual nights available) typically averages 3 to 1, but may be as high as 10 to 1 in certain seasons when key objects are optimally visible.

The CFHT

The Canada-France-Hawaii Telescope (CFHT) is a 3.6 metre optical/infrared telescope located on the summit ridge of Mauna Kea, the large dormant volcanic peak on the `Big Island' of Hawaii, at an altitude of more than 4000 metres. It is owned and operated jointly by Canada (42.5% share), France (42.5%), and the University of Hawaii (15%).

Since its commissioning in 1979, the CFHT has been the flagship of Canadian optical astronomy and one of the premier laboratories in all of Canadian science. The summit of Mauna Kea is above almost half the Earth's atmosphere and surrounded by the Pacific Ocean on all sides. The quality of astronomical observation from this location (numbers of clear nights, darkness of the night sky, and especially the sharpness or "seeing quality" of the star images) is unexcelled anywhere on the surface of the Earth.

The dome of the Canada-France_Hawaii Telescope sits high atop the 4000-metre summit of Mauna Kea on the "Big Island" of Hawaii

CFHT Corporation, Photo courtesy Jean-Charles Cuillandre, CFHT

The CFHT operates at optical and near-infrared wavelengths. Its digital cameras and spectrographs -- all built jointly by the Canadian, French, and Hawaiian partner laboratories -- are continually improved with the advance of technology in detectors and instrument design.
Canada's astronomers use about 150 nights per year on the CFHT. Among the many prominent achievements by Canadian teams with the CFHT are:

(1) The pioneering of techniques for enormously more precise velocity measurement of nearby stars (a decade ahead of other teams which are now using these techniques to find planets around nearby stars);
(2) The first clear observational evidence that supermassive black holes commonly exist at the centers of large galaxies;

(3) The investigation of the oldest stellar populations and globular cluster systems in the Milky Way and other nearby galaxies, uncovering the earliest threads of galaxy formation;

(4) The "red-shift" survey of galaxies that showed that the galaxy population evolves with cosmic time, having had much higher cosmic star formation rates in the past;

(5) Evidence for a "low" cosmological density of matter in space, Ω_0 =0.3, established from the measured motions of galaxies in large clusters.

Another key legacy of the CFHT to astronomy worldwide is its influence on telescope design and image quality. CFHT has led the world in demonstrating the possibilities for superb seeing quality obtainable with a large ground-based telescope. This is accomplished through innovative adaptive optics cameras. Today, the designs of all new ground-based telescopes incorporate these same techniques for image quality control, including the new generation of 8 metre telescopes optical/infrared telescopes.

Innovation in the use of instruments continues. In the near-infrared, an "adaptive optics" camera, built jointly by Canada and France, is routinely used whose image quality rivals that of the Hubble Space Telescope over small fields of view. The primary mission of the CFHT for the first half of the next decade will be to deploy new cameras (Megaprime, WIRCAM) which will provide an unparalleled, wide field of view with high image quality. Canadian astronomers will also continue to exploit its optical spectrographs, which allow the precise study of stellar properties at extremely high resolution and address several key areas in the physics of stars including stellar oscillations, magnetic fields, and winds.

Gemini

The Gemini project -- the newest facility and acknowledged highest priority in Canadian optical/infrared astronomy for the next several years -- consists of two new telescopes with mirror diameters of 8 metres: the first is on Mauna Kea, and the second on Cerro Pachon in the northern part of Chile. Together they will allow Canadians to view the entire sky, including objects unique to the southern hemisphere that are unobservable from CFHT or Gemini North. Canada holds a 14.2% share in Gemini, making it the third partner after the United States (47.5%) and the United Kingdom (23.7%); smaller shares are held by Australia, Argentina, Brazil, and Chile.

Canada's share on both telescopes combined corresponds to about 90 nights per year.

Among the several 8 metre class telescopes now being built or in operation, the Gemini project is unique in its design goals for the highest possible image quality achievable from the ground. The Mauna Kea telescope, Gemini North, is now complete and in its commissioning phases. Gemini South will be commissioned in mid-2000, with scientific operations for both telescopes scheduled to ramp up to their full levels by 2005 as instruments gradually come on line.

The Gemini North dome, here seen on the summit of Mauna Kea, is the newest addition to Canadian optical and infrared astronomy. This 8 metre telescope will produce newer and deeper studies of star-forming nebulae within the Milky Way galaxy, and unprecedentedly detailed views of remote galaxies.

Image from Gemini Webpage gallery, NOAO/AURA and Canadian Gemini Office

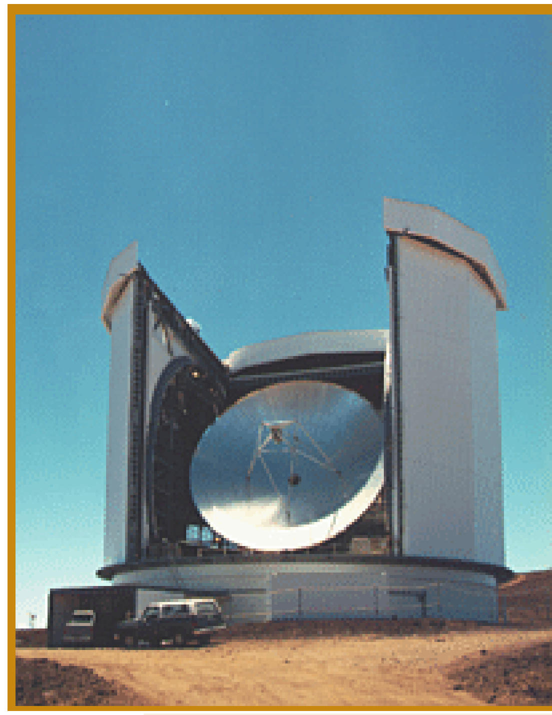
The superb new primary mirrors for the Gemini telescopes are among the finest ever manufactured (the Gemini North mirror has an rms surface precision of 15 nanometres, as if the entire Atlantic Ocean had average waves one centimetre high!) The largest scientific gains to be delivered by the Gemini instruments will be at near-infrared wavelengths, between 1 and 5 microns, which is much less well explored than the optical regime. The Gemini designs are targetted towards narrow to moderate fields of view at high spatial resolution. Combining their larger light-gathering power with their improved image quality, the Gemini instruments are expected to produce performance gains of at least a factor of 10 over the older 4 metre class telescopes. Through the NRC, Canada is building a pair of multi-object spectrometers as well as an adaptive optics system for Gemini.

The Gemini instruments will provide Canadian astronomers with deep and exciting new probes into the numbers and ages of faint stars within the Milky Way galaxy; the sites of star formation and the physical characteristics of protostars; the internal motions and dynamics of protostellar disks; the chemical compositions of the oldest stars and thus the state of the primordial gas in galaxies; and the spatial distributions, sizes, and luminosities of high-redshift galaxies in the early Universe.

The JCMT

The James Clerk Maxwell Telescope (JCMT), also located on Mauna Kea, is the largest of the present generation of radio telescopes designed to work at "sub-mm" wavelengths (0.3 - 1.3 mm, at the high-frequency end of the radio band). The diameter of its primary mirror is 15 metres. The JCMT was built jointly by the two largest partners, the United Kingdom and the Netherlands, and is financially supported by the UK, Canada, and the Netherlands. Canada has been a 25% partner since the telescope was commissioned in 1987.

The submillimetre region of the electromagnetic spectrum lies between the far-infrared and the microwave wavelengths. Until the past decade, the sub-mm and mm wavebands were among the few spectral regions not well explored by astronomers because of the special observing conditions and instruments required. However, these wavelength “windows” into the universe contain critically important information on “cool” objects including the planets, protostellar disks, and the molecular clouds where new stars are forming. Also, cosmologically remote objects such as extremely distant galaxies or quasars recede from us at such high speed that much of their emitted light is redshifted into the sub-mm region. Thus the capabilities of the JCMT are extremely well suited to the study of the formation of both stars and entire galaxies.



The James Clerk Maxwell Telescope (JCMT) on Mauna Kea is a 15 metre diameter mirror designed to capture extremely short-wavelength (sub-millimetre) radio radiation. While in operation, the mirror is normally covered with a protective mylar membrane (shown here unrolled)

Photo courtesy Henry Matthews (JCMT/HIA)

The JCMT is equipped with an array of detectors that target the narrow spectral lines characteristic of the cool gas molecules in space. These spectra carry information about the chemical composition, temperature, density, and motions of the emitting clouds of gas. Another kind of detector, known as SCUBA, measures how much radiation is coming from large sections (wavebands) of the spectrum. These measurements are highly sensitive indicators of the amount of cool interstellar dust within these clouds, which in turn provides an important measure of the total amount of gas and of the cloud temperatures.

Canadians have done prominent work with the JCMT in studies of our solar system, in mapping star-forming complexes of gas clouds in our own Milky Way galaxy, and in understanding important new aspects of galaxy formation in the Universe.

Representative samples of recent discoveries by Canadians are:

(1) The first high-quality (SCUBA) images of a remarkable, dusty filament within the Orion molecular cloud whose structure may imply that filamentary clouds are threaded by novel, helical magnetic fields;

(2) A deep sub-mm survey of a group of high-redshift galaxies, that revealed an unanticipated population of very luminous star-forming galaxies when our universe was very young;

(3) A detailed study of the recent bright Comet Hale-Bopp, providing the most comprehensive study ever of a comet in the mm/sub-mm spectral region. The behaviour seen in the emission of many molecules is providing new insights into the nature of comets as primordial structures within our solar system.

Canadians compete vigorously for access to this unique facility. Just as for the CFHT and soon Gemini, NRC/HIA staff not only use the telescope, but provide Canada’s share of the development and construction of its highly specialized detectors. Thus the JCMT has been directly responsible for building up a new base of users and forefront technological skills.

Equally important is that the JCMT has created for Canada a strategic science and instrumentation springboard from which to move into the next generation of mm and sub-mm telescopes, including the Atacama Large Millimetre Array discussed below.

3.2 National Observatories

Several "on-shore" observatories are owned and operated entirely by Canadian institutions. These places are smaller and less expensive to operate than the higher-profile international observatories described above, but they nonetheless play important strategic roles:

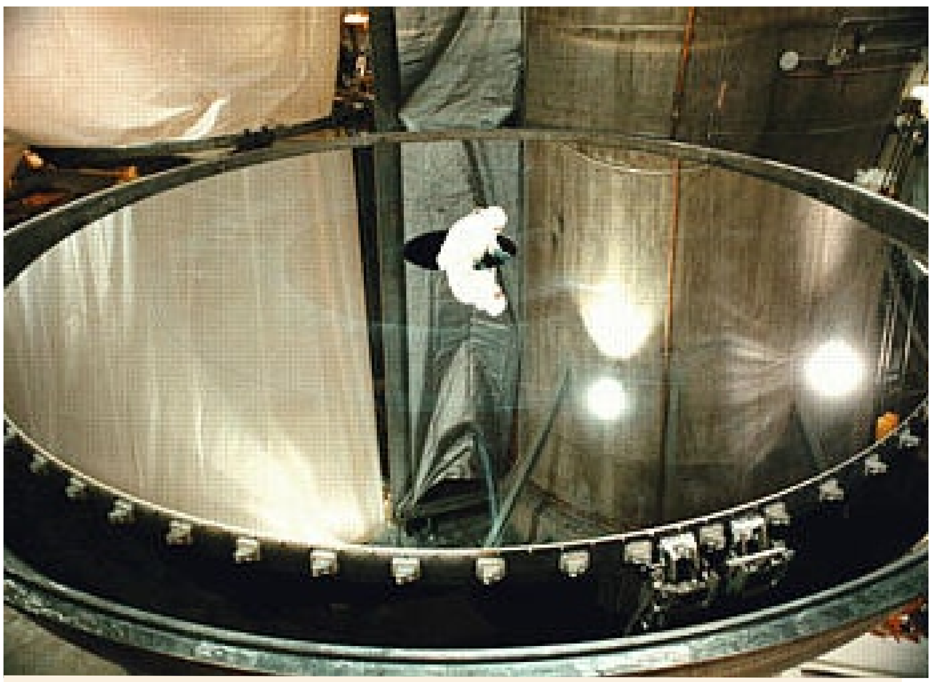
(1) At the offshore sites, observing time is at a premium and individual astronomers may only obtain a few nights (or even hours) of data per year. Domestic facilities provide large blocks of time for more time-consuming programs of a different nature such as surveys, long-period monitoring, or student thesis projects.

(2) Although the domestic telescopes themselves may be modest in size and cost, they can still be equipped with first-rank instruments (cameras, spectrographs, and detectors) and can therefore serve as testbeds for novel instrument development

(3) The domestic facilities provide an irreplaceable way for researchers, students, and senior staff to acquire hands-on, locally accessible training with instrumentation techniques.

(4) These facilities provide excellent outlets for public outreach: members of the public can conveniently visit them and gain first hand impressions of professional observatories.

The domestic observatories operated by the National Research Council also provide a highly effective vehicle for research and engineering linkages between NRC instrumentation staff and the training of students and postdoctoral fellows in the universities.



The 8 metre diameter mirror for the Gemini telescopes are among the finest ever made

Image from Gemini Webpage Gallery NOAO/AURA and Canadian Gemini Office

The DRAO

The Dominion Radio Astrophysical Observatory (DRAO), a division of HIA, is located outside Penticton, BC. It is primarily directed toward radio astronomy in the decimetre wave band, and it is responsible for the operation of the DRAO Synthesis Telescope and a 26 metre single dish telescope.

The DRAO Synthesis Telescope, the heart of its current operation, consists of seven 9 metre paraboloid dishes on an east-west line 600 metres long. It is sensitive to both the radiation from the neutral atomic hydrogen emitted by cool gas clouds in our Galaxy, and the synchrotron emission (from free electrons spiralling around magnetic field lines in interstellar space) from more energetic sources such as the expanding gas clouds from supernova explosions. Its wide, 2.5 degree, field of view coupled with its arcminute spatial resolution, makes this array unique.

Most observing time on the Synthesis telescope is currently devoted to mapping, in unprecedented detail, a strip straddling the equator of the Milky Way, 70 degrees long and 9 degrees wide. This Canadian Galactic Plane Survey (CGPS) involves a consortium of 55 astronomers, including 43 from Canada and involving astronomers from 11 other countries. It is training 11 doctoral students, has attracted 9 postdoctoral fellows, and is supported by an NSERC Collaborative Special Projects Grant of $800 000 over five years. The project links with a still larger international consortium combining data from other observatories at other wavebands to develop a comprehensive, multi-wavelength, global view of the interstellar medium in the plane of our Galaxy.

The Synthesis Array at the Dominion Radio Astrophysical Observatory in Penticton. The multiple radio antennas, all pointing up to the same location in the sky, are used to build up a combined image more detailed than any single antenna could produce.

Image courtesy Russ Taylor (University of Calgary) and DRAO/HIA

DRAO has become a leader in other directions as well: it is a world centre for the development of radio interferometry (the technique of electronically combining signals from several individual telescopes to build up a composite image of an object at a far greater level of detail). First-rank groups dedicated to correlator and receiver development are also associated with DRAO. These form a key resource in the Long Range Plan to drive the engineering development for the advanced radio telescopes coming in the next decade.

Several other projects hosted at the DRAO include the development of a correlator for a focal plane array heterodyne receiver for the JCMT, and engineering studies for the internationally proposed Square Kilometre Array (SKA). DRAO staff have also been especially active in the training of graduate students and post-doctoral fellows in radio astronomy, primarily through cooperative links with campuses such as the University of Alberta and the University of British Columbia.

The DAO

The Dominion Astrophysical Observatory (DAO) north of Victoria, BC, is home to HIA headquarters and most of its subdivisions. It is also the site of two optical research telescopes: the 1.8 metre Plaskett Telescope (in continuous operation since 1918) and the 1.2 metre McKellar Telescope (in operation since 1962). The 1.8 metre has a moderate-resolution spectrograph for spectroscopy of stars, as well as cameras for imaging in the optical and near-infrared. The 1.2 metre is devoted to high resolution spectroscopy, directed at measuring the motions and chemical compositions of stars. It was used for developing the planetary search technique now in use world wide, and has played a central role in establishing the international stellar velocity standard system due to its exceptionally stable spectrograph.

The dome of the 1.8 metre Plaskett Telescope at the Dominion Observatory, Victoria

Photo courtesy HIA/NRC

Both telescopes are open for community use, are fully subscribed,and are operated at very low expense. They support a wide variety of scientific programs, involving students and guest observers from both Canada and abroad. Recently retired DAO staff have also developed innovative ways to supply community astronomers with “contract observing” to keep costs down for potential clients.

In the pre-WWII era, the Plaskett telescope held prominence as one of the three largest telescopes in the world.Though it now occupies the role of a supporting player, it is an excellent illustration of the way that a telescope can continually, and inexpensively, be revitalized by careful redesign and deployment of new instruments.

A recent project on the Plaskett telescope that has gained considerable international interest is its long-term campaign to determine orbits for Near-Earth Asteroids, ie., those whose orbits cross over the Earths orbit. Such asteroids could inflict huge damage if they strike the Earth. While several telescopes discover such asteroids, the Plaskett telescope is the largest one devoting systematic effort to tracking their paths and thus to determine asteroid collision probabilities. The Plaskett telescope is also central to the DAO public outreach program.

The CADC

The Canadian Astronomy Data Centre (CADC) is a small but visionary group within NRC’s Herzberg Institute and supported in part by CSA. It is one of the most cost-effective and widely used resources in Canadian astronomy. Its development of innovative data handling techniques now leads the entire international community.

Data archiving is the provision of a capability to save data, to save all relevant information about the data (the metadata), and to be able to present these data (and metadata) to users in a comprehensible, searchable, and retrievable form. The CADC supplies the community with electronically accessible archives of data from principal telescopes including the CFHT, JCMT, Gemini, and also the HST through a special arrangement with the Space Telescope Science Institute.

For the near future, the CADC plans to provide pipeline processing for a subset of the data from MEGACAM on the CFH telescope; known as the TERAPIX project. The CADC is a participant and will archive the products of MEGACAM/TERAPIX for the general astronomical community.

In addition to this primary mandate, however, the CADC has, over the last decade, evolved methods for linking and searching the primary databases in a huge variety of ways. "Data mining" is a new CADC initiative to develop the next generation of tools for accessing and correlating data from many archives simultaneously. In essence, an archive is useful only if it has powerful tools with which to access and explore it.

Data mining will allow any astronomer to collect all the measurements of a given object over all telescopes and wavelengths; or to extract and correlate all data for any definable category of objects from all databases. This new research tool will fully utilize the combined capabilities of computation, database management, and modern archiving principles.

The funding situation of many of these excellent CADC programs is currently rather dire, and immediate action will be needed if they are to move forward.

University Observatories

Small- to mid-range optical telescopes are also operated by some of the Canadian universities, primarily for the use of their local astronomy research groups and departments, student training, and instrument testing. Prominent examples of these are the 1.6 metre telescope at the Observatoire du Mont Megantic operated jointly by the Université de Montréal and Université Laval; the 1.8 metre at the David Dunlap Observatory of the University of Toronto; the 1.2 metre at the University of Western Ontario; and the 1.5 metre at the University of Calgary. These observatories play central roles in public outreach programs, an issue to which we return in chapter 7.

3.3 Astronomy from Space: Currently Funded Programs

Modern astronomy makes extensive use of space-based telescopes, and most developed nations are heavily involved in both ground and space-based observatories. A superb example of the power of this complementary approach is the combination of the ground-based Keck observatories (the 10 metre optical/infrared telescopes on Mauna Kea) and the orbiting Hubble Space Telescope (an optical/ultraviolet telescope with a 2.5 metre mirror). While the HST provides superb optical images with the finest available sharpness and depth, the Keck mirrors provide much larger photon collection rates that allow astronomers to study the spectra and physical characteristics of the ultra-faint objects discovered by HST.

There are strong reasons for designing a combination of ground and space-based observatories. The instrumentation packages used to detect and analyze the light collected by the ground-based telescopes can be state-of-the-art, and they can be tested, modified, and replaced over much shorter turnaround times than for satellite telescopes. They can be built in larger sizes and greater varieties than telescopes in orbit. A network of ground-based telescopes can therefore be much more versatile and strategically controllable by comparison with the high-risk, high-payoff space missions. Costs are far lower, and instrument failures or operational problems are not catastrophic, as they are for space-based missions.

The satellite observatories, on the other hand, provide the only way to see celestial objects in the wavebands that do not penetrate the Earth's atmosphere: gamma-ray, X-ray, most of the ultraviolet, and some sections of the infrared and radio bands. Their other immense contribution is that observations outside the Earth's atmosphere provide us with the sharpest possible (highest resolution) images at short wavelengths (optical, ultraviolet, and beyond), unblurred and undistorted by the atmosphere, and unaffected by weather.

Canada's role in space science utilizing satellite observations began with the Alouette program in the early 1960's and has continued with a series of small satellites designed to study the upper atmosphere and near-Earth environment. Canadian industry has played an important role in all of these, and many have involved international partnerships. All space initiatives are now supported through the Canadian Space Agency (CSA).

The current CSA-supported satellite missions for astronomy include:

(a) **VSOP**, a Japanese-led orbiting radio Very Large Baseline Interferometry (VLBI) antenna. Canada has played a pioneering role in this project in having provided crucial technology such as the S2 recorders and correlators, with a VSOP correlator center based in Penticton. In turn, these developments have opened new opportunities for contracts to build correlators for the JCMT, and for possible other international projects. The Canadian VLBI community is also carrying out the bulk of the VSOP Sky Survey.

VLBI techniques on the ground and in space have given us our closest look yet at the central regions of active galaxies that harbour supermassive black holes. As an example, the present VSOP mission can study a region that is a thousandth the size of the finest resolution scale of the HST!

(b)**MOST**, is a novel, stellar-seismology, micro-satellite being built by Dynacon under the guidance of a UBC-led science team, and funded under the existing CSA small payloads program. It is designed to monitor the minute stellar oscillations down to the level of those studied on the Sun; an amplitude of a few parts per million. These levels are currently beyond ground-based detection limits. The observations will be used to help pin down stellar structures and ages to an accuracy known only for the Sun at the present time.

c) **FUSE**, a far-ultraviolet spectroscopic telescope, one of the NASA Explorer series. The HIA together with COMDEV of Cambridge ON, have helped design and construct several instrument and staff the operations center. FUSE, which obtained its first spectra in August 1999, will open up new views of the hottest stars and gas in our galaxy, and is specially designed to be able to measure the deuterium abundance in a wide variety of local and moderately distant galaxies. This will provide very important constraints on cosmological models.

(d)**ODIN**, a combined aeronomy/astronomy satellite in collaboration with Sweden, Finland, and France. It is designed to probe the upper atmosphere of the earth in the sub-mm region, and also to look out into space to examine molecular constituents of the interstellar gas. Odin will search for water and oxygen in the Universe, two of the most important molecules in the chemical network of the interstellar medium, and two of the major ingredients in the origin of life.

(e) **BAM** (Balloon-borne Anisotropy Measurement), an experiment led by a UBC team, will measure the CMB radiation with a balloon-borne 1.7 metre telescope.

3.4 A Personnel Profile of Canada's Research Community

The NRC and University Communities

Research astronomers in Canada are employed either by the universities or by NRC's Herzberg Institute. The universities provide the primary base of researchers and the training grounds for young people in the field; while the NRC staff and laboratories provide the combined technical and research expertise to construct and operate our primary observational facilities. Both of these arms of the community are essential and complementary to one another, and there has been a long tradition of shared effort between them.

The decade just past saw an unfortunately long string of budget cuts imposed by the federal and provincial governments on both NRC and the universities across the country. These cuts have now seriously damaged crucial aspects of Canadian astronomy. The LRPP has identified several points of potential critical failure (see chapter 5):

1. Much of the experimental instrumentation work in the universities has withered away, with serious overall losses to our infrastructure. Small instrument labs (typically one senior scientist plus two or three technical staff or research associates) are now maintained at only a handful of universities (Laval, Montréal, Toronto, Calgary, UBC). The staff at these remaining places are individually excellent but do not have the resources for extensive training or design programs, or for bidding on major instrument work for our international partnerships.

2. The opportunities for NRC staff scientists to carry out their own primary research have been severely reduced. Many of these scientists are powerful researchers and the loss to community science productivity has been quite significant. In mid-1998, the HIA underwent a comprehensive peer review and site assessment. The conclusions

from the review committee report strongly reinforce the message that the HIA is playing a technologically essential and high-level strategic role in the community, but that its activities must be rebalanced to include a stronger primary research component at its highest levels.

Competitiveness Issues: Strengths of Canadian Astronomy

Measures of the international competitiveness of the Canadian astronomy community include (a) their ability to generate international collaborations and obtain awards of observing time; (b) research grant leveraging and other awards; and (c) the relative presence of Canadian authors in the international literature, including the level of citations to published work.

University astronomers gain most of their funding throughthe normal NSERC competitions for Research Grants, Equipment Grants, and Major Facilities Grants. For the Space and Astronomy community (Grant Selection Committee GSC17), approximately 160 university faculty are supported at an average Research Grant level of $36,000, making up 2.2% of the NSERC research grant budget.

Individual Research Grants are “leveraged” by gaining research funds of other types, from NSERC, government, or industry sources. (Leverage is defined here as the number of additional dollars gained for each awarded research grant dollar.) Statistical data collected in 1997 by NSERC staff show that, for the Space and Astronomy community,

(a) The overall leverage ratio for all grantees in 1995/96 was 1.5,

(b) The leverage ratio for the upper 30% of Space and Astronomy grantees was 2.8. This latter group ranked 4th out of 18 NSERC disciplines in science and engineering.

Furthermore, these statistics do not take into account the equivalent value of the awards of observing time gained every year by the astronomers in the community. The operating expenses for a major telescope such as the CFHT are approximately $20,000 per night, so a normal three-night observing run each year is equivalent to a “grant” valued at $60,000. A large fraction of this money returns to Canadians in the form of observatory staff salaries and instrument development projects.

Canadian astronomers are versatile researchers who actively seek out ways to use publicly available resources in other countries, notably the American facilities (NOAO, NRAO) which generously maintain open-access policies by annual competitions based on scientific merit. Canadians obtain time on these facilities which typically adds up to the sum of our ownership shares on the CFHT and JCMT. Canada reciprocates by applying open-access policies to its own shares of CFHT and JCMT, though these can never add up to the amounts we gain by competitive access elsewhere. Furthermore, we cannot expect generous “open skies” policies to be maintained in the future for the new generations of facilities built on more extended international partnerships (next chapter).

An excellent example of the international respect gained by Canadian astronomers is their presence on many HST projects with American or European PI's. Since the 1994 refurbishing mission (and as a tribute to US generosity in holding open international competitions), no less than 39 of the individual HST programs have had Canadian principal investigators; equivalent to 2.3% of the total time on HST.

NSERC-funded scientists have also done extremely well in garnering prominent awards and fellowships. The relative numbers of such items as Steacie Fellows, Steacie Prize winners, Killam Memorial Prize winners, and NSERC University Research Fellows and Women's Faculty Awards won by astronomers over the past two decades are anywhere from 2 to 5 times larger than the fraction of the NSERC research grant budget allocated to Space and Astronomy. The Canadian Institute for Advanced Research (CIAR) makes its single largest investment in cosmology.

In both numbers and impact, the scientific productivity of Canadian astronomers is strong. In the USA-based Astronomical Journal and Astrophysical Journal, the leading world journals in the discipline, the ratio of recent papers by Canadian authors relative to American authors is 18% and 7% respectively even though the American comparison group is more than 10 times larger. A recent British funding council bibliometric analysis finds that Canadian astronomical research ranks third in citations per paper (6.0), just behind the USA (7.0) and the UK (6.5).

A 1993 study carried out in Holland compared the budget and impact levels of astronomy research in 15 OECD countries. Notably, in "value per dollar" measures such as the ratio of total research budget to numbers of publications and citations, Canada ranked first on this list, with cost per citation a factor of five below the median. In terms of research budget for astronomy relative to total national population or GNP, Canada ranked last on the list, sitting a factor of four below the median (see also the comparisons listed in the following section). Part of the reason for this ranking is that Canada has invested less than most of the other OECD countries in observatories and infrastructure, especially in space and satellite astronomy which has a higher "dollar per photon" cost level than ground-based astronomy.

3.5 Funding of Astronomy in Canada and Abroad

The total annual funding for NRC's Herzberg Institute, in fiscal year 1999/2000 is 15.5 Million dollars. This breaks down as:

1. Salaries, benefits, on-shore operations, minor capital: $ 8.9 M

2. Contributions to overseas facilities: $ 6.6 M

At the same time, the total funding for NSERC funding of astronomy in the Space and Astronomy division, in the same fiscal year is 6.3 Million dollars. This is distributed between:

A. Individual research grants: $ 5.9 M

B. Equipment grants (major and minor): $ 0.4 M

Thus, the total NRC/NSERC funding in space and astronomy is 21.8 Million dollars per year. The precise CSA number is still uncertain at this writing but is approximately $8 Million per year.

Table 2 : Current Astronomy funding for various Countries

Country	GDP per capita	Population (millions)	Annual Astronomy spending: Amount (millions)	Annual Astronomy spending: Amount ($ CA per capita)	Source	Comments
USA	30 200	270.3	1 700		NASA	includes all space missions related to astronomy and planetary science, excludes Mars Surveyor, lunar and atmosphere missions, and launch support services
			181		NSF	astronomical sciences
			76		Private funding	very uncertain - Carnegie, etc
			1 957	**7.24 total**		
France	22 700	58.8	370	6.2		
Italy	21 500	56.8	320	5.63		
UK	21 100	59	288	4.88		
Germany	20 800	82.1	393	4.79		
Australia	21 400	18.6	28	1.51		
Canada	21 700	30.7				
			6.28		NSERC	Space and Astronomy (*not including proposed LRP funds)*
			0,4		FCAR	Research Grants and support for Mont-Mégantic
			15.5		NRC/HIA	current spending (*not including proposed LRP funds)*
			8		CSA	
			30.18	**0.98 total**		

In Table 2 we briefly compare Canadian funding levels for astronomy with selected countries which are prominent on the world level. The figures in the last two columns are in Canadian dollars, and give the estimated total annual expenses of each country on astronomical research and also funding per capita. Since the GDPs in each country are similar, the comparisons would not change significantly if they were also adjusted for GDP level. The United States leads all nations with more than $7 per capita annual investment. Furthermore, the total for the USA is likely to be an underestimate since it does not fully account for the significant amounts of project funding from university consortia and private organizations.

Ranking next are the European countries at typically $4 - $5 per capita. (As noted earlier, the USA and Britain enjoy the two highest citation rates for papers in the astronomical literature, followed closely by Canada). Canada, at roughly $1 per capita funding for astronomy, lags well behind these leading nations. Its closest comparison is with Australia, which also has a traditionally strong community in ground-based astronomy on a frugal budget, but very little involvement in space-based astronomy.

A high fraction of the investments in the USA and in the European Common Market countries comes through a healthy investment in satellite and space astronomy (NASA in the US, ESA in Europe; we emphasize that contributions of these agencies to missions that are not central to astronomy such as upper atmosphere and Earth studies, lunar missions, Mars Surveyor, and launch support services have been explcitly excluded from the figures quoted in the Table). Although the cost of a full-fledged space program is clearly large, the returns through national growth in technology, economics, and impact on science are concomitantly large.

It should be noted that precise comparisons between any two countries are difficult because of individual differences of detail in funding systems and research programs (for example, in the USA some of the NSF and NASA funding goes into partial faculty salaries and overhead expenses, whereas in Canada these are part of the base budget for universities). Thus all the figures in Table 2 should be viewed as uncertain to roughly 20 percent. However, the global differences between Canada and the nations leading the list are so large (a factor of 7 for the USA and a factor of 5 for the United Kingdom) that they mark fundamental differences in the degree to which astronomy is supported. Even when the comparisons are restricted to ground-based facilities, Canada ranks last on this list.

There is little doubt from these statistics that Canadian taxpayers are obtaining a significant bargain for the research dollar that they do spend on astronomy. Canada is, however, in a different league than the countries that have embraced this subject on a much grander scale. Our relatively small investment in astronomy has also denied the nation the full economic, cultural, and technological benefits that go along with complete partnership in the many exciting astronomy missions. These benefits are discussed further in Chapters 7 and 8.

3.6 Training, Employment, and Demographics Issues

Astronomy and astrophysics graduate students and postdoctoral fellows are being trained in about 15 universities and institutes across Canada. Far from being an esoteric and abstract field, modern astronomy is now one of the broadest of the physical sciences. Students of this subject must acquire a wide spectrum of tools which borrow from, and combine, all the physical sciences: atomic, nuclear, subatomic, and condensed-matter physics; thermodynamics; relativity; molecular and atomic chemistry; chaos theory; geology and geophysics; and even elements of biology. Handling the very large data-rates now being generated at the telescope requires outstanding skills in quantitative image processing, database management, archiving techniques, and statistical methods. These high-level computing techniques cut across many discipline boundaries in science, technology, and medicine. For theoretical modelling, advanced computing and mathematical techniques have also moved to center stage as we piece together the multiple processes at work within the astrophysical systems, and construct computer simulations of them.

Most important of all, modern astronomy and astrophysics teaches flexible, lateral thinking and the ability to solve a wide range of difficult problems. The very richness of astronomical phenomena promotes broad vision because solutions must assemble interpretations from widespread techniques and from evidence that is sometimes sketchy and always incomplete.

Employment statistics within the Canadian community were traced in a 1996 survey done by CASCA. Records were gathered for 121 Ph.D. students who graduated from Canadian astronomy programs in the interval 1976 to 1992, a nearly complete sample for that period. Of these, 42% went on to research-type positions in universities or observatories; 7% to teaching positions in colleges or schools; and 27% to a variety of jobs in industry, government, or university support staff, usually for computing systems management or consulting. Most of the remaining 23% were in temporary but high-level research positions such as postdoctoral fellowships or research associates.

The most notable “non-astronomy” outlets for graduates are in technology or industry positions involving image analysis, data management, optics, and computing techniques. Some notable examples include (a) the Canada Centre for Remote Sensing in Ottawa, which analyzes satellite and aircraft imaging data of the Canadian land surface and has hired a total of seven astronomy PhD’s since its inception; (b) the Institut National d’Optique (INO, Laval), which employs more than 30 staff involved with space and astronomy instrumentation; (c) the oil industry in Calgary, which has employed many university graduates with astronomy training; and (d) risk-analysis groups in major Canadian and international banks. These graduates are attractive precisely because of their wide problem-solving and technical abilities.

ASTRONOMY AND ASTROPHYSICS IN CANADA TODAY

An elegant spiral galaxy, ESO 269-57, in the southern hemisphere sky

Image from Very Large Telescope (VLT) at the European Southern Observatory (ESO), Chile. Copyright ESO

An Australia-based study published in 1999, traced the career paths of 897 PhD astronomy graduates in 1975-1994, from four countries (USA, Canada, Australia, and Holland). The study finds that roughly 45% of the graduates obtain long-term research-based positions (tenured university faculty, or observatory scientists), 20% continue in soft-money positions, and 35% enter areas outside astronomy. These numbers are consistent with the CASCA study.

At present, the Canadian astronomical community comprises about 160 researchers in staff or faculty positions, including both university and NRC members. There are, in addition, about 150 more young researchers who are postdoctoral fellows, research associates, and senior graduate students and who contribute strongly to the environment of research activity within the discipline. The recent NSERC statistical report (Research Grants Program: Discipline Dynamics, October 1997) shows that about 30% of its primary research faculty and grantholders will retire and therefore leave the system in the next decade. There is every indication that astronomy and astrophysics are highly regarded in Universities, and that these retirements will be replaced in due course with talented young Canadian and internationally prominent individuals. In addition, the implementation of the proposed LRP plan will require (and indeed, will stimulate) an increase in the astronomy and astrophysics faculty complement at universities across the nation.

In summary, the Canadian astronomy and astrophysics community is active, prominent, and working at the forefront in many sub-fields within our discipline. Its record of achievement is clear, and the potential for its even greater success, unparalleled. Canada, with an imaginative allocation of new resources, is poised to make its mark on the era of cosmic exploration that will undeniably dominate our coming century. Should we decide to join this exciting endeavour, our research universities and laboratories will adjust and recruit many new outstanding individuals at all levels in response to this vision.

We turn, therefore, to examine the outstanding new world observatories that will make this possible; observatories to which Canadian astronomy and astrophysics could contribute enormously, given the chance.

CHAPTER 4

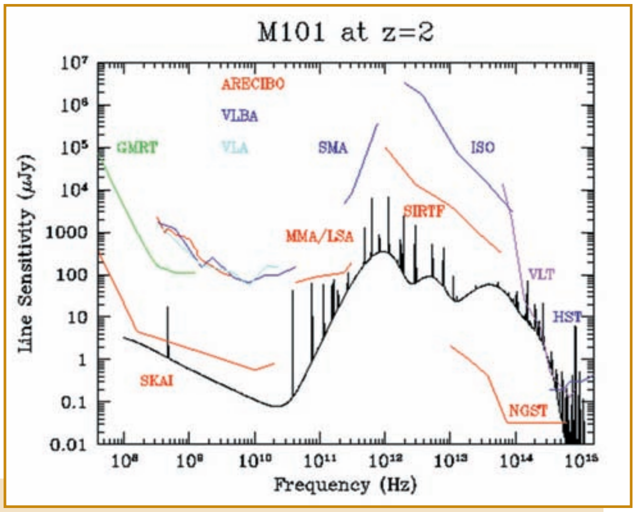
Future Prospects: World and International Observatories

4.1 World Observatories

In this chapter we describe the major new observational facilities Canadian astronomers will need in order to attack the astrophysical questions about the universe posed in Chapter 2. These tools must cover all wavelengths from radio through to the ultra-violet, and will combine space-based instruments with ground-based ones. They will be designed and operated in such a way that astronomers in many different sub-disciplines will be able to do observations with them. Many of the technological challenges inherent in constructing these observatories will also present many new and exciting prospects for Canadian industry and technology.

First we discuss “World Observatories”. These are the new observatories that will be constructed in the next two decades, on a scale which no single country or small group of countries could afford by themselves, and which will not be duplicated by other consortia. These world observatories will truly be one of a kind and are expected to have a revolutionary effect on our understanding of the universe. They come with correspondingly large price tags: their capital costs are expected to be in the range $500M - $1B US. Investments at these levels will be shared among many nations with the goal of constructing uniquely powerful telescopes which will define the limits of our knowledge for the next decade and even beyond. We divide the world observatories into first generation ones that are expected to become operational in the period 2001-2010, and second generation ones that may be commissioned in 2011-2020.

To place the power of these facilities in context, we show the sensitivities of several of them as a function of wavelength in the accompanying graph. The frequency range along the horizontal axis runs from the radio region on the left hand side, through the sub-mm range, into the infrared and on up to the optical and ultraviolet at the right hand end. The vertical axis indicates the flux (energy intensity) emitted by an astronomical object such as a distant galaxy. The lines in the plot show the smallest flux an object can emit and still be detected by a given telescope. Thus the lower lines are the ones from the most powerful facilities. For example, we see that NGST



Sensitivity of several World-level telescopes as a function of frequency. The black line shows the typical radiation energy received from a (very) distant galaxy. The red lines towards the bottom of the plot show the sensitivities of several of the future world facilities. The other colored lines show the sensitivities of current facilities. Lower is better! Large tick marks on the vertical axis correspond to a factor 10 in sensitivity.

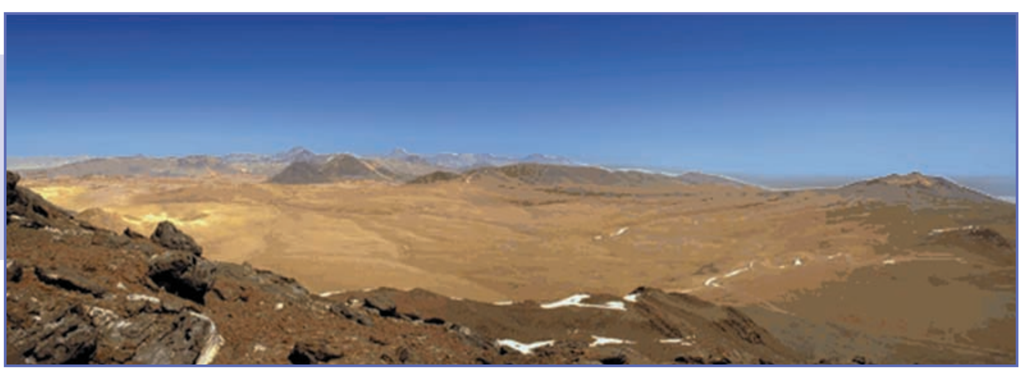
(the major successor to the Hubble Space Telescope) will be able to observe objects 10 times fainter than HST at optical wavelengths; at longer wavelengths in the infrared, it will be able to detect objects up to 100,000 times fainter than can be seen from an 8 metre class telescope on the ground (labeled VLT).

First Generation

Atacama Large Millimeter Array (ALMA)

ALMA will be, by far, the world's most powerful radio telescope operating at mm and sub-mm wavelengths, both in terms of sensitivity (ability to detect extremely faint sources) and angular resolution (ability to "see" the fine detail of structure in those same sources). It is the top priority in ground-based astronomy for the American and European astronomy communities over the coming decade and it is easy to see why. ALMA will be able to detect cosmic sources up to a thousand times fainter than is possible with any existing mm telescope. It will also produce images of these sources with at least ten times higher resolution (down to one hundredth of an arcsecond) than either the Hubble Space Telescope or the Very Large Array in New Mexico. This is equivalent to resolving a house on the Moon! As currently envisaged, the telescope would comprise about 64 antennas, each about 12 metres in diameter. It would operate at wavelengths from 10 mm down to 0.35 mm in the sub-mm band. The current partners include the USA, Europe, and possibly Japan; other potential partners are now expressing strong interest. Canada's scientific and technological capabilities are extremely well matched to ALMA.

The science goals for ALMA are conveniently summarized at http://www.mma.nrao.edu/science. ALMA will focus on millimetre wave observations



Proposed site for ALMA, at Llano Chajnantor at 5000 metres altitude in the Chilean desert.

Photo by S. Radford, NOAO

of dense gas, where it will be able to peer into dense, dusty regions that are invisible at other wavelengths. These regions are exactly where most stars are formed. ALMA will be able to detect the molecular gas from star forming regions at completely unprecedented distances and depths. At the distance of the nearest young stars in our Galaxy, the resolution will be approximately equivalent to the distance between the Sun and the Earth, enabling us to observe and understand how the gas and dust collapse to form a protoplanetary system. On a larger scale, the mapping of molecular clouds throughout the Milky Way and beyond will pinpoint the sites of star formation complexes to give a more complete picture of this process on many scales. ALMA will, for the first time, allow us to study the molecular clouds of many distant galaxies in astonishing detail.

Artist's sketch of the ALMA array. *Courtesy ESO*

In the larger universe, ALMA will permit us to examine the epoch of galaxy formation much more directly than ever before, bringing into view the gaseous raw material out of which the first stars formed in the pre-galactic clouds. One of the standard tracers of molecular gas conditions is the carbon monoxide molecule (CO) in its various forms. In a one hour exposure, ALMA will detect CO emission in protogalaxies at redshifts of 10 or more, corresponding to lookback times of about 97% of the age of the universe. These earliest pre-galactic structures may be visible only in the sub-mm band as highly redshifted infrared emission from dust, and we will gain our first views of them with ALMA. With existing instruments such as JCMT, it is currently possible to see only the rarest, most luminous protogalaxies at these extraordinarily large lookback times; ALMA will bring into view the full range of protogalaxies of all types.

In a wider context, the capabilities of the ALMA will beautifully complement those of NGST, which will allow us to study related phenomena in the optical and IR bands, and at comparable angular resolution. To some degree the complementary instruments will probe these phenomena in differing stages of their evolution, thus providing a more complete picture than any one of them could, alone.

Canada is well poised both scientifically and technically to become an effective international partner in the ALMA project. Scientifically, Canada's strength emerges both from its user base associated with the JCMT as well as its general research strength in subjects such as the interstellar medium, star formation, galaxy formation and evolution, and cosmology. From a technical standpoint, Canada can contribute especially in receiver technology, and in the complex correlators which will be necessary to process the information from 64 antennas and thousands of frequency channels. In addition, Canadian industry has considerable experience associated with telecommunications, the fabrication of telescope structures, and the cryogenics needed for the receivers.

Next Generation Space Telescope (NGST)

The Next Generation Space Telescope is an ambitious project led by NASA, with active participation from the European Space Agency. It is designed to take the next huge step beyond the remarkably successful Hubble Space Telescope program. By launching an 8 metre diameter telescope to an “L2 orbit” (a stable location in space 1.5 million km from the earth in the direction away from the Sun), the background light from the bright glow of the earth's atmosphere is avoided. The telescope will be shielded from the Sun and the Earth by a large deployable sunshield, allowing the whole telescope to cool to 35 degrees above absolute zero. This gives the telescope extraordinary sensitivity at infrared wavelengths.

A possible design for the Next Generation Space Telescope. The telescope mirror will deploy after arriving in orbit, and the large sunscreen allows the rest of the telescope to cool down and hence be able to measure exceedingly faint objects at infrared wavelengths from 0.6 - 30 microns.

Courtesy NASA / GSFC

It is anticipated that NGST will allow us to see the highly redshifted light from the very first clusters of stars formed in the early universe and thus to witness a key moment in the history of the cosmos. As well as this "first light", NGST will reveal how stars and gas are then assembled into galaxies during the first few billion years of the universe, give us vital information about the most important physical processes in star formation, and study the cool protoplanetary disks out of which planetary systems are made. Other highlights range from the detection of supernovae at distances that will allow us to measure the geometry of space-time, to studies of the Kuiper belt cometary objects. Details on the wide range of science that can be done with NGST can be found at the Canadian project scientist's web site: http://astro.utoronto.ca/~lilly/NGST/index.html.

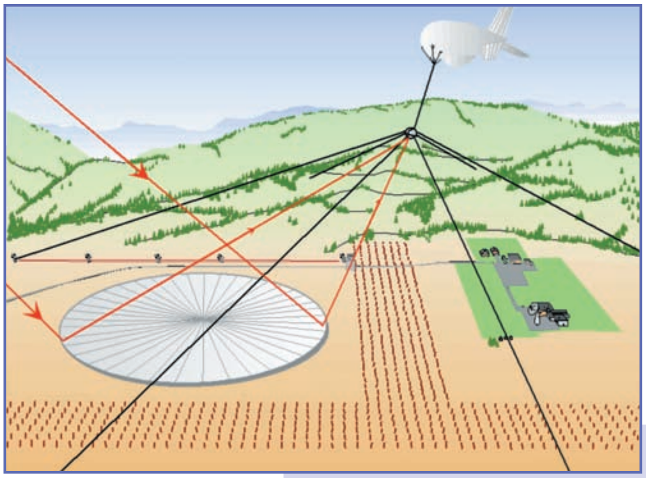
The Canadian Space Agency has shown strong interest in participating in NGST. The Canadian astronomical community unequivocally supports this initiative because it superbly matches many of its primary scientific goals for the next two decades. The CSA is currently funding three instrument studies (two of which are led by NRC staff astronomers), and also some industry led studies of spacecraft components, in order to define possible Canadian contributions to the NGST observatory. Active Canadian involvement in the project from these early stages puts us in an excellent position to reap all the benefits from this extremely ambitious and high profile project, in the form of science, technological spin-offs, outreach to the public, and education.

Second Generation

Square Kilometer Array (SKA)

The Square Kilometer Array is a project of giant scale that is still in the planning stages. As the name suggests, its goal is to build a radio telescope (sensitive to radiation with wavelengths of a few cm and longer) with a collecting area of a square kilometer. For comparison, the collecting area of the world's largest current radio telescope built into a crater at Arecibo (Puerto Rico), is thirty times smaller. However, rather than building a single huge collecting dish, the enormous aperture size of the SKA would be distributed in the form of many individual antennas scattered in a geometric array hundreds of kilometers across, to achieve the highest possible angular resolution. With this design, the SKA would exceed the existing most powerful array - the Very Large Array (VLA) in New Mexico by an increase of 100 in sensitivity, and 10 in angular resolution.

A summary of the SKA science goals can be found at http://www.ras.ucalgary.ca/SKA/science.html. A major highlight will be the detailed mapping of gas within individual galaxies, with the 21 cm emission line from atomic hydrogen. Such mapping can be done out to redshifts of 3, corresponding to lookback times of 80% of the age of the universe. The SKA will also allow us to trace the gas into the very central regions of active galaxies such as quasars and giant ellipticals, giving accurate measures of the masses of the huge black holes lurking at their centres. Cosmologically, perhaps the most interesting observation planned for the SKA will be the detection of structure in the early universe, in the "Dark Era" after the Cosmic Micro-wave Background Radiation was emitted but before the galaxies formed, as seen through the highly redshifted emission of the primordial atomic hydrogen.



Concept for the Canadian Large Adaptive Reflector showing the innovative balloon-borne feed. An eventual SKA may be built out of many of these array elements distributed over hundreds of kilometers.

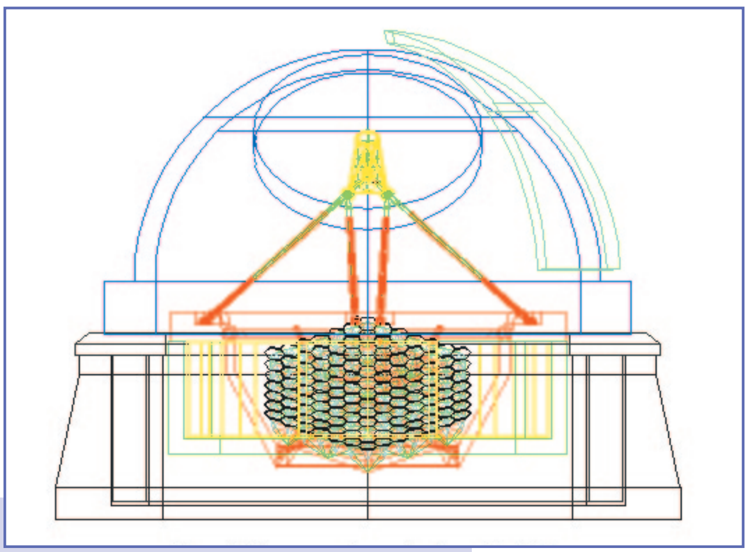
Courtesy NRC

The SKA will be a powerful tool for investigating star formation as well. Its role here will be to study a set of the emission lines from the heavier molecules which characterize the coldest, densest regions of protostellar gas clouds. In addition, the SKA is uniquely suited to the study of the ionized gas as well as the more predominant atomic hydrogen within the collimated jets of protostars. It can also determine the magnetic field strengths in star forming regions which may control the sequence of events in star formation. Because of its uniquely large collecting aperture, the SKA would also be a suitable instrument for detecting extrasolar planets and even in the search for extraterrestrial intelligence.

Among all the new facilities discussed here, it is in the SKA project that Canada may play a leading technological role. Because of the huge scale of SKA – a large array of individual antennas, each one of which is itself enormous – conventional radio antenna designs would be prohibitively expensive. An entirely new technology is needed to construct a telescope on this scale. Canadian astronomers are pioneering a revolutionary new concept for building the individual antenna elements of SKA capable of working at wavelengths as short as 1 cm. This imaginative design is referred to as the Large Adaptive Reflector (LAR). It employs a large, adjustable, but nearly planar antenna surface mounted close to the ground, and a tethered airborne (balloon mounted) collector at the focal point of this surface. The concept designs suggest that steerable antennas up to 200 metres in diameter may be constructed. The Phase A study shows that the control of such a structure is feasible. Phase B development of scaled prototypes of the reflector and airborne aerostat are now required. Just as for ALMA, Canadian expertise is at hand for the receivers and the correlators which will eventually be needed for SKA.

Very Large Optical Telescope (VLOT)

The immense power of the NGST to detect ultra-faint objects particularly at infrared wavelengths will eventually require one or more complementary telescopes on the ground. A ground-based “partner” to NGST will have the task of obtaining spectra and even deeper optical images of these objects – cosmologically remote galaxies, faint stars in galaxies millions of parsecs distant, and extremely faint objects in our own Galaxy, such as protostellar disks, brown dwarfs, Jovian planets, and neutron stars. There is no other way to determine the nature of such objects that are at the faintest limits of what we know to exist. The light-gathering power of such a telescope will have to exceed that of any instrument on the ground today, as would its image quality. This Very Large Optical Telescope (VLOT) would likely have a segmented-mirror assembly with an equivalent diameter of 25 metres or larger.



Candidate 30 metre VLOT design. Transparent front elevation of the ELT.

Many serious technical issues need to be addressed before such a project can be started. However, the timescale for all large-telescope projects is typically 15-20 years from Phase A design to the completion of construction. Initial concept discussions for VLOTs began within the international astronomical community in 1998, so it is reasonable to predict that a VLOT would be in operation by 2015-2020, just at the far end of our Long Term Plan. In order to illustrate the rapidly growing importance of such a project on the international stage, we note that the National Optical Astronomical Observatory in the US is already proposing that a 25 metre segmented mirror VLOT go into operation around 2010, which would in turn act as the prototype for a truly giant 100 metre scale facility five to ten years later. Designs for comparably large telescopes are also being energetically pursued in Europe. It is therefore essential that if Canadian scientists are to take leadership roles in appropriate parts of a VLOT project, seed funding for technical studies must start now.

One promising area of Canadian expertise which would be well suited for VLOT design goals is in adaptive optics. This technique reduces the size of stellar images seen by a telescope by correcting for the turbulent layers of the upper atmosphere which blur the star image. This image degradation effect is dramatically worse at shorter wavelengths (optical) than at longer ones (infrared). Such techniques will be essential for the VLOT, and will have to work at a more advanced level than any of today’s adaptive optics systems. Future innovations which will be required for VLOT include the use of multiple laser beacons to sense the turbulence in the atmosphere, and also algorithms to take that information and deform multiple mirrors conjugated to the different layers in the atmosphere. Canada is currently a world leader in this area, having built with France the most successful currently working system (the Adaptive Optics Bonnette in regular use on the CFHT), and having won the contract to build the adaptive optics system for the 8 metre Gemini project. Ultimately, a VLOT could deliver 10 times better spatial resolution than even NGST over moderate fields of view, a truly exciting prospect. When combined with a collecting area of at least 25 metre in diameter, it will yield performance gains almost two orders of magnitude over any optical telescope in existence today.

4.2 New International Observatories

Wide-Field 8 metre Telescope

The world-level observatories described above are likely to be designed for ultra-deep penetration into the remote universe. But we must also have instruments that will survey large regions of the sky. There are two major reasons for this. First, it is becoming increasingly necessary to measure genuinely large samples of objects to trace out the statistical patterns that define much of the structure of the cosmos. For example, millions of distant galaxies must be measured for their large-scale distributions in cosmological space to be established; hundreds of thousands of halo stars must be searched for the pattern of heavy-element enrichment in the early history of the Galaxy to be established; and thousands of star-forming nebulae and protostars must be surveyed for the rules of star formation to be deciphered correctly. Second, it is only by accumulating huge statistical samples that the genuinely rare, exceptional objects can be reliably found – the oldest and least chemically enriched stars, the largest or smallest galaxies, the most extreme quasars and black holes, or the most massive protostars. These rare cases represent the extremes of Nature which teach us where the new frontiers of physics will be found.

A night time view of the Gemini dome under construction.

Courtesy NOAO / AURA and Canadian Gemini Office

For optical/infrared astronomy, the CFHT 3.6 metre will fill the need for survey-mode science for the next few years. Astronomers will use the CFHT in combination with the Megaprime instrument (an optical camera with a one-degree field of view, unrivalled by any current large telescope) and with WIRCAM, the proposed wide-field infrared camera. The high-dispersion spectrographs will also continue to provide first rank tools for areas such as stellar astrophysics. These instruments will keep the CFHT in a competitive position for several years.

It is very important, however, that our community begin immediate construction of a state-of-the-art 8 metre class telescope which would take over the role of survey-mode observations.

Combining its larger collecting area with improvements in image quality, such a telescope would outperform CFHT by a factor of 10, and it would also be less expensive to operate than the older-style optical observatories. A wide field 8 metre telescope will beautifully complement Canada's investment in the Gemini program, which is designed for a different set of capabilities such as deep infrared imaging and spectroscopy with relatively small fields of view. If this new capability becomes available around 2005, our astronomical community will stay competitive with other astronomical communities in the total number of nights available on a front rank telescope. Adding a wide-field spectroscopic capability would be a natural complement to the imaging programs, making possible true 3-dimensional surveys of large parts of the universe. A new 8 metre class telescope should also incorporate designs for very high dispersion spectrographs that would take the current instruments on CFHT to a new level. The vigorous group of optical spectroscopists within our community would employ these for a wide variety of important scientific programs such as studies of the surface physics of stars.

Canadian science goals for a wide-field 8 metre will include the ability to study the evolution of galaxy formation and galaxy clustering at distances reaching well past current frontiers, out to redshifts of 3 or more when the main epoch of galaxy formation was taking place. Large-scale samples of galaxies at moderate redshifts will permit the first truly comprehensive surveys of weak gravitational lensing and thus will lead to the mapping of mass in space. The evolution of galaxy properties – their numbers, size, and star formation rates – can be followed from early times right up to the present day. For stars within the Galaxy, large samples of young stars can be traced out to define the initial mass distribution (IMF) of star formation, and productive searches can be carried out for the lowest-luminosity stars, including white dwarfs and brown dwarfs. NGST, ALMA, or the other facilities described above will not address such questions effectively because of their small – albeit extremely deep – fields of view. However, a WF8m would be highly complementary to all the other telescopes discussed here.

In order to keep Canadians competitive in the post-CFHT era, and to enable optimum use of our partnerships in ALMA and NGST, rapid deployment of this new telescope is urgent. Although its optical design will be slightly different from the Gemini 8 metres, its capital cost will be similar to Gemini. While it will certainly be necessary to seek out international partners to share the cost of this facility, we also believe it is crucial that Canada should seek to be a substantial partner (roughly 40%) of a WF8m collaboration. As a major partner, we can strongly influence the design and scientific operation, and provide the community with the sheer numbers of nights per year of observing time that it will need in the post-CFHT era.

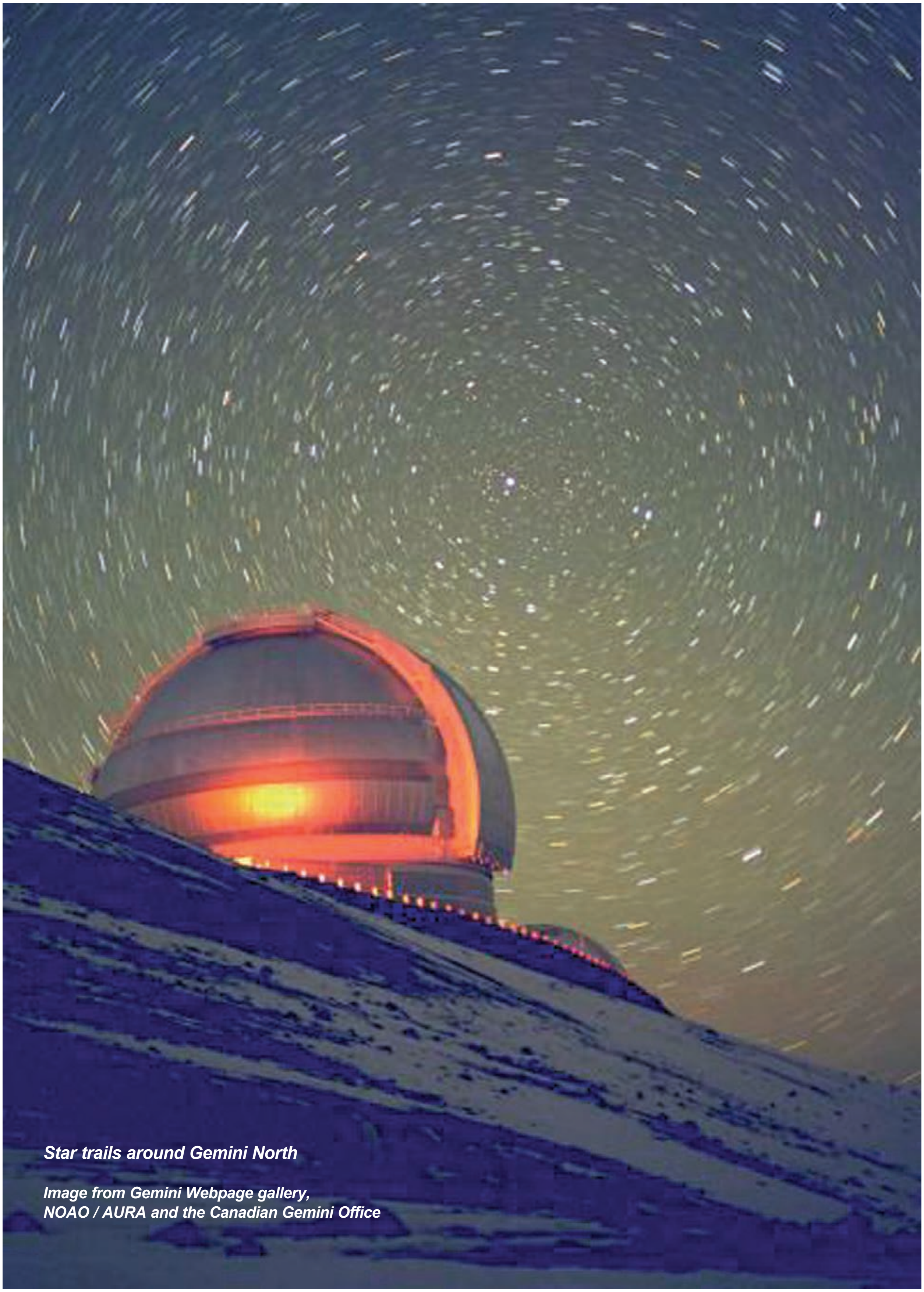
FIRST/Planck

The FIRST/Planck mission is led by ESA. As the dual name suggests, this mission packages two satellites into a single launch. Details on the science goals of these missions can be found at: http://www.physics.ubc.ca/~halpern/jssa/FIRSTplanck.html. The FIRST (Far InfraRed Space Telescope) satellite will study the sky at wavelengths from the far infrared to the sub-millimetre which lie between the regimes of ALMA and NGST. Even in the driest ground-based sites such as the Atacama desert, absorption of far-infrared and sub-millimetre radiation by atmospheric molecules (mainly water vapor) is effective enough to shield the sky from view, so at these wavelengths, satellite observations are irreplaceable. FIRST is a major satellite observatory which will give us this capability. The spectroscopic instruments on FIRST will observe a wide variety of molecules in other galaxies and will be a leader in the study of astrochemistry in the 21st century.

Planck is a very different mission. It is aimed at the Cosmic Microwave Background Radiation (CMBR), which is the tremendously redshifted light that was emitted during the early universe before any stars or galaxies existed. Planck will map the CMBR light filling the entire sky in exquisite detail, far greater than was accomplished by the COBE (Cosmic Background Explorer) NASA mission of a decade ago. The tiny fluctuations in intensity – no more than a few parts per million – in this background light are an imprint from the earliest seconds of the Big Bang. These fluctuations, over the course of time, then grew to form the huge structures (clusters and superclusters of galaxies) that we see across the universe today. The cosmological model parameters described in Chapter 2, such as the average mass density, vacuum energy, and fluctuation spectrum, leave their characteristic traces in the distribution of primordial gas. Thus, direct measurements of the amplitudes and scale sizes of these small irregularities in the CMBR provide one of the most important direct routes we have to finding the correct cosmology model.

Space Very Long Baseline Interferometry

The successful scientific and technical returns of the VSOP space VLBI mission will lead to new possibilities in the coming decade. Two examples of these are the Japanese /ISAS led, VSOP II mission as well as the US/NASA led, ARISE mission. The reader may find more information about the latter at the website http://www.arise.jpl.nasa.gov . One example of the superb angular resolution that will be possible with the latter experiment is its ability to resolve the central region of our closest active galaxy, Centaurus-A, to less than a tenth of an AU in size (a few light days). NASA will require the wide bandwidth VLBI technology in which Canada has the expertise.



Star trails around Gemini North

*Image from Gemini Webpage gallery,
NOAO / AURA and the Canadian Gemini Office*

CHAPTER 5

Plan for Astronomy and Astrophysics in Canada to 2015

5.1 Basic Philosophy

The wellspring of astronomy and astrophysics is basic human curiosity about the universe, and our place within it. Any viable plan for the development of astronomy, therefore, must be founded upon the commitment to explore its most exciting new frontiers. This chapter presents the recommendations of the LRPP for the development of astronomy in Canada over the next 10 to 15 years. The vision articulated here is all encompassing and argues for a substantial increase in Canada's investment in these fields, bringing it a bit closer to the far greater per capita expenditures of the other developed scientific nations with whom we collaborate and trade. As we shall show, these expenditures return to Canada in many ways: scientifically, culturally, and technologically.

What is now proved was once only imagined.

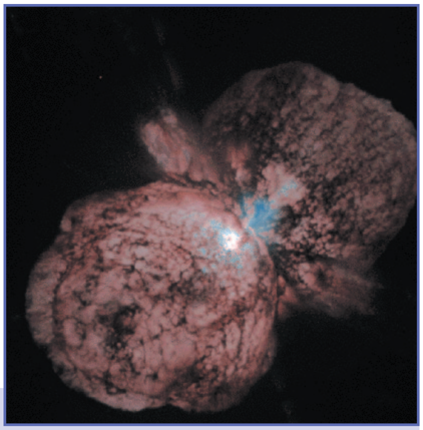
William Blake

The LRPP plan rests upon the following basic principles:

•**Fundamental Research:** The major international theme of astronomy and astrophysics in the early 21st century will be the origins of structure in the universe (see Chapter 2). The frontiers of research in this era are highly likely to be planet formation, star formation, galaxy formation and evolution, and cosmology. We should focus our scientific efforts on making important advances of the highest calibre in these fundamental areas.

Ultimately, it is the wonder and mystery of the universe that inspires astronomical research. Throughout history and especially in the latter half of the 20th century, astronomy and astrophysics have been a major stimulus to the development of other branches of fundamental science, mathematics, and engineering; an exciting part of school and university curricula; and a driver for the growth of technology and industry of the most varied kinds. Given the large impact that astronomy can and does make upon science, technology, and culture, the starting point of any excellent plan for astronomy must be the identification and pursuit of its most fundamental, unsolved problems.

•Complementarity: A profound understanding of the origin and evolution of structures in the universe requires a multi-wavelength approach to astronomy. No single telescope can be the complete tool with which to address all of these fundamental issues. Rather, a carefully designed, interwoven set of ground and space-based observatories and facilities that complement one another's scientific capacities must be a cornerstone of any ambitious astronomical plan.



Billowing pairs of gas clouds are seen in around the supermassive star Eta Carinae in the southern sky. This HST image captures detailed features in the dust and gas ejected from near this young star.

Image by Jon Morse (University of Colorado) and NASA

These goals for astronomical exploration present tremendous challenges to the design of new facilities and research capabilities. Cosmic structures are complex and their physical properties cannot be adequately understood by making observations in only a narrow band of wavelengths. From planets outwards to cosmology, the formation of structure involves the organization of matter from barely perceptible beginnings to a dazzling variety of mature structures. A suite of observatories and instruments will be required in order to explore these issues

•Impact: In order to derive the maximum scientific, technological, and cultural benefit from the plan, we must ensure a deep intellectual involvement in any project that we join as international partners. It is essential to enter into projects with sufficient financial and human resources to permit Canadians to influence the directions of the project, and to place Canadian astronomy and astrophysics at the forefront of the field.

The ultimate challenge to our community is to create both the vision and the tools that will be capable of making major discoveries in astronomy and astrophysics well into the coming century. A good plan must also ensure technological and industrial involvement that leads to sound economic growth, and provide for extensive outreach and educational programs that will benefit the public's appreciation and enjoyment of astronomy.

5.2 Initiatives

The LRPP considered a large number of proposals for future initiatives over the period Sept. 1998 to June 1999. Unfortunately, only a subset of these many, often very worthy proposals for new instruments, facilities and even institutes, could be chosen. In addition to the principles noted above, the LRPP was guided by the depth of community support for each proposal, as well as by the extent of existing community strength and infrastructure that could sustain it. We do not further describe, in this report, the initiatives that the LRPP did not recommend for funding. **Therefore, it is important to realize that all of the recommendations made in this report are to be regarded as being essential to Canadian astronomy and astrophysics.** Among the entire set of essential recommended programs, the LRPP further identified subgroups of projects whose failure to be funded would lead to particularly severe and permanent damage to the future of Canadian astronomy and astrophysics. We denote these subgroups in a "top priority" category, which are denoted by an asterisk in Table 1.

In making our recommendations, we note that major new world observatories and international facilities are in a qualitatively different funding level than the smaller, but often extremely important projects, studies, and instruments. We acknowledge this distinction by dividing all facilities recommendations (summarized in Table 1) into two distinct bins: major new facilities, and moderate size facilities and projects. In addition to new facilities, the plan makes recommendations in funding for other critical areas such as people, computation, and outreach initiatives.

The facilities required by Canadian astronomers over the next 10-15 years fall into three categories; world, international, and national observatories. Each has a strategic role in the overall plan. Whereas astronomy more than twenty years ago tended to be dominated by the national observatories within each country, this gave way over the last twenty years to successful international collaborations of small groups of countries in the construction of facilities such as the highly successful CFHT and JCMT. Astronomy is currently undergoing a "phase transition'' wherein most of the world's astronomical community will be combining its resources to construct a small number of one-of-a-kind world observatories. These are each targeted at specific wavelength regions and taken together, will provide a complementary array of capabilities to address frontier problems. These truly major observatories will dominate the astronomical landscape; if Canada is not a participant at this new level it will be relegated to the astronomical side-lines. It is crucial that Canada play a vital part in the first generation facilities, and make every effort, now, to play a leading role in the planned second generation facilities.

It is the overall conclusion of the LRPP that if Canada does not participate in these most powerful, new world observatories, our excellent current reputation in astronomy and astrophysics would be relinquished within a decade, and many economic opportunities and social benefits, lost.

A.1 World Observatories: First Generation (2000 – 2010)

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

ALMA is poised to become one of the key instruments of the coming century. Planned during the 1990's, and likely involving the bulk of the astronomical communities in Europe, the United States, as well as possibly Japan, it will have the capability to perform highly sensitive observations at millimetre wavelengths. This array will have a spatial resolution that is ten times better than HST, making it a highly attractive research tool for a wide variety of astronomers. ALMA will contribute substantially to the understanding of all aspects of science emphasized by our plan. It will allow us to study everything from planet formation to the microwave background in cosmology. It will provide a unique insight into the process of star and planet formation in being able to map out the conditions within protostellar disks to an accuracy of better than 1 AU in nearby systems.

In studying the properties of gas and dust in the nearby universe, as well as at high redshifts, it will provide the means to study the emergence of galaxies and to compare their gaseous properties over vast portions of the universe. It will provide an excellent tool to push out to the era in which galaxy formation was prominent.

The LRPP found wide and deep support for entry into ALMA in the Canadian astronomical community. Regardless of research field, or wavelength of specialization, astronomers across the country attach great importance to our participation in this project. This view of our community mirrors that of our international colleagues. ALMA enjoys the top ranking in the major astronomical communities on the planet. It is ranked as the highest priority in the European astronomical community, and was rated as the top priority of the 1991 US decadal review (the Bahcall report). The report of the subcommittee on radio astronomy (see Volume II, A.1) also strongly argues for its adoption in the coming decade.

The outstanding expertise at NRC's Herzberg Institute for Astrophysics (HIA), especially in the areas of submillimetre and millimetre wave receivers and technology such as correlators, would allow Canadian astronomers to play an important role in the construction of this new facility. The close partnership that already exists between the NRC and university radio astronomers will be greatly enhanced in joining this project. It is anticipated that the opportunities offered by entry into ALMA will stimulate the hiring of not only more millimetre wave radio astronomers, but other observers and theorists as well at universities across Canada in the coming decade. Furthermore, both ALMA and SKA present opportunities for AGRA- Coast, which constructed the domes for the Gemini Telescopes and has proven its ability to build radio telescopes.

• ***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, collaborative 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 moderate size projects.

These groups will be of central importance in furthering Canadian participation in several projects such as ALMA and the Square Kilometre Array (SKA) over the coming two decades. The involvement of the correlator group in the planned NRAO, VLA extension would be an excellent use of our expertise in correlators and could serve as a good entry card into ALMA.

• ***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.

Astronomy in the last decade has taken huge strides as a consequence of the results that have come from satellite observatories. The most famous is the Hubble Space Telescope (HST) which has both fired the public imagination and driven the development of new technologies on a grand scale. The capabilities offered by the NGST are beautifully complementary to those provided by ALMA (see Volume II, C.2). The LRPP has found broad based support for NGST that cuts across all sub-disciplines in our community, and enjoys a status very similar to ALMA. This support is based in part on the fact that NGST will increase the sensitivity of observations at infrared wavelengths (between 1 – 30 microns) by factors of 10 to 1000 relative to present ground-based telescopes. It will enable the investigation of planet and star formation, the nature of the stellar initial mass function, galaxy formation out to redshifts of 20-30, the distribution of dark matter (through gravitational lensing) and the geometry of the universe (through sensitive supernova searches). These abilities, when complemented by ALMA's ability to chart the evolution of molecular gas, will help drive a virtual revolution in our knowledge of structure formation in the universe on many different scales.

The LRPP wishes to underline the fact that our astronomical community, in not being involved in the construction of major space-based scientific observatories in the past, lacked significant influence on the scientific direction of the project and technology development other than in data archiving. Space-based astrophysical research has been a tremendous scientific and technological stimulant for agencies such as NASA, the European Space Agency (ESA), and Japan's NASDA. We now have a unique opportunity to redress this problem and to employ Canadian scientific, instrumental, and technological talent towards participation in the successors to these observatories, such as the NGST.

A.2 World Observatories: Second Generation (2010 - 2020)

The Square Kilometre Array (SKA) radio telescope and the Very Large Optical Telescope (VLOT) are the two world observatories whose construction will likely commence after the completion of ALMA and NGST. Presently, SKA is in a much more advanced stage of design. Both of these second generation observatories could be as critical to astronomy in the second decade of the new century as ALMA and NGST are in the first.

• ***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 an SKA.

SKA will complement the wavelength regions covered by ALMA and NGST. For cosmology , it will allow us to push out much farther back in time, allowing us to study star formation in the early phase of the universe back to the appearance of the very first stars. Canadian astronomers have defined what may be the most economical, and exciting design for the SKA observatory that would operate at higher frequencies and feature an array of 30, Large Adaptive Reflectors . Each reflector would be a superb radio telescope in its own right, consisting of a 200 metre adjustable dish on the ground and a tethered balloon 500 metres above the dish that carries the radio receivers. Objects are tracked across the sky by controlling these tethers.

The LRPP concludes that the science opportunities and potential of SKA are very high, comparable to those of ALMA. Furthermore, if the LAR design for SKA is adopted, it would vault Canada into a leading role in the project. SKA may be among the most important second generation world facilities after 2010. SKA and the LAR are still experimental and need further development and testing, for which there is broad community support. Therefore it is most important that this project be provided with the resources needed to explore designs and given the means of constructing a single, stand-alone telescope prototype (known as CLAR, see Volume II, A.2 and A.3) should this be the recommendation of the Phase B review.

• ***The LRPP strongly recommends*** that a team be quickly established to develop designs for a Very Large Optical Telescope (VLOT). This study should be one of the highest priorities among moderate size projects. Canada should join in a world team in this effort. A rigorous review of the results as well as the science goals and design status of the VLOT should then occur (roughly five years).

• ***The LRPP recommends*** that a development envelope be established that would help to fund the construction of a world, VLOT prototype, if recommended by the mid-course review.

• ***The LRPP recommends*** that Canada position itself now for entry into the construction of a VLOT.

The status of world ground-based, optical astronomy will not become completely clear until the NGST flies. Nonetheless, a ground-based telescope of at least 25 metres diameter could play a similarly complementary role to the NGST, as does the current 10 metre optical Keck telescope for the HST. While design concepts for a VLOT are still in their infancy, it is important to begin serious thinking now for this world observatory that may become a reality towards the end of the second decade of the next century.

The planning for a possible world VLOT has barely begun in the international community. This is highly advantageous to Canada because we have the opportunity to enter this project on the ground floor. Construction of a VLOT would not likely begin until the middle of the second decade, with operation commencing around 2020 (see Volume II, B.1). Among the possible designs, the LRPP recommends that a 25 metre design also be developed. A VLOT of this size is the minimum size that would complement the NGST while representing a natural and logical upward step from the current generation of 8 metre telescopes. The high resolution imaging capabilities of NGST would be complemented by the better light gathering power of VLOT.

Canada's expertise in optical and infrared astronomy could have great impact on the design of a VLOT. Our astronomical community should be prepared, through investment in basic conceptual design and eventual involvement in prototype development, to play a leading role in this type of facility. The LRPP recommends that planning for a VLOT be completely decoupled from any necessary reliance upon the CFHT site. The long term future of both of these facilities depends upon several issues whose outcome cannot be predicted at this time.

ALMA and SKA, as well as NGST and VLOT will constitute a complementary, amazingly powerful, tetrad of observatories whose operation will allow an increase in sensitivity of factors of 100 to 1000 over an immense range of wavelengths.

B. International Observatories

International facilities, defined as limited international partnerships among a small number of partners, have played a strong role in astronomy over the last twenty years. The international facilities to which we have major commitments are Gemini, CFHT, and JCMT. As has already been discussed (see Chapter 3), the two 8.0 metre Gemini telescopes will open exciting new avenues for exploration and research to Canadian astronomers over the coming decade in all of the major scientific areas discussed in our plan. There is a pressing need, however, to plan for the roles that the 3.6 metre CFH telescope and JCMT will play in the coming decade.

• ***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.

Gemini will provide exciting capabilities in a forefront telescope in the new 8 – 10 metre era that is upon us. They have involved much of our optical/IR instrumental expertise and are poised to make outstanding scientific discoveries.

• ***The LRPP recommends*** that our community quickly obtain significant participation (40 %) in the construction and operation of a new optical/infrared, 8 metre class telescope. Wide-field capability should be given priority.

There are two critical, long standing, concerns of optical and infrared astronomy in the Canadian community that cannot be alleviated by our important but relatively small presence in Gemini. These issues are:

1. The total number of 8 metre telescope nights that Canadian astronomers can access on Gemini is just a small fraction of what will be needed in the coming era. While our community enjoyed 150 nights per year at the forefront CFH 3.6 metre telescope over the last decade, at our present level we will only have 90 nights of 8 metre time on both Gemini telescopes combined. This reduction of time that Canadians have at a front-line telescope seriously threatens the viability of the community if not addressed quickly.

2. The CFH 3.6 metre telescope will lose its edge as a front-rank instrument, almost certainly after 2006. The performance gain of the new 8 metre class of telescopes over the 4 metre class is roughly a factor of 10 thanks to the combination of increased light gathering power and superior image quality. The operational costs per square metre of telescope are considerably less for an 8 metre telescope than the CFH 3.6 metre telescope.

The design for a new 8 metre optical telescope should allow for the ability to incorporate instruments to carry out high resolution spectroscopy. These are essential for many of the science goals presented in the plan including stellar astrophysics.

The scientific objectives of a wide-field 8 metre (WF8m) telescope are beautifully complementary to the existing 8 metre Gemini telescopes. Gemini gives our community the ability to do high resolution studies of particular targets requiring a smaller field of view. The proposed WF8m emphasizes a wide-field optical design that is optimal for carrying out surveys in cosmology, galaxy formation, and star formation studies where progress depends upon accumulating large sample sizes.

The LRPP has found wide support for a WF8m project across the entire Canadian astronomical community. The science case and preliminary ideas for such a facility may be found in the advisory paper (Volume II, B.2). It is essential that, as a member of such an international project, Canada be able to control a significant number of nights if it is to continue to rank among the leading nations in optical and infrared astronomy. It is also imperative that this project begin quickly as our community has an urgent need for more observing time on an 8 metre class telescope.

• ***The LRPP recommends*** that the MegaPrime camera, as well as the wide-field infrared camera, WIRCAM, be funded at CFHT. Priority for resources invested in the CFH 3.6 metre telescope should be given to a new 8 metre telescope as needed, beyond 2006.

CFH 3.6 metre telescope operations and instrument plans for the next decade feature new cameras for high quality, wide-field imaging. The MegaPrime project is a optical instrument of this type and will be in operation in 2002. The WIRCAM is an imaging camera that operates at near infrared wavelengths and is intended to be constructed within the next 3 years. Together, these instruments will drive first rank survey results for a variety of scientific programs until the middle of the next decade. There is, at the present time, no available funding for WIRCAM and this is urgently needed if CFHT is to remain competitive even during the next few years.

There is wide recognition in our community that CFHT collaboration has been a resounding success. However, we do not have the resources to operate both the present 3.6 metre CFHT and a new 8 metre optical telescope. While the first choice of Canadian astronomers would be to carry the “spirit of CFHT” forward into a new 8 metre collaboration, financial constraints in France make this unlikely at present. Therefore, the LRPP recommends that the Canadian astronomical community maintain its current commitments to the CFH 3.6 metre telescope, including support for the MegaPrime project as well as WIRCAM. If the resources for continuing CFHT operations beyond 2006 come into competition with those needed for Canada’s role in a new 8 metre telescope, then priority must be given to the 8 metre.

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

Currently, the SCUBA instrument is making pioneering advances through surveying young luminous galaxies and regions of star formation. In many ways, JCMT over the next 5 – 10 years will produce its most outstanding results; comparable in importance to the science that flowed from CFHT over the last decade. Canadian astronomers have made outstanding contributions to JCMT project. First rank discoveries will continue to flow from the JCMT until ALMA becomes operational. After ALMA comes on line however, it will supersede JCMT in scientific impact. If the resources for continuing JCMT operations beyond 2009 come into competition with those needed for Canada’s role in ALMA, then priority must to be given to ALMA. This is necessary to ensure Canada’s strong intellectual partnership in the latter project.

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

The Planck satellite will measure cosmological parameters that are crucial to the development of the fields of cosmology and galaxy formation, such as the Hubble constant and the density of the Universe. FIRST will supply deep new views of forming galaxies and stars, and the interstellar gas, at infrared wavelengths. All of this information will be important for the construction of models of galaxy formation and evolution (see Volume II, C.3). This observatory will provide essential cosmological information that will complement that obtainable with the NGST. Given Canadian expertise in theoretical and observational cosmology, entry into this mission is highly desirable to our community.

•***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 Very Long Baseline Interferometry technique makes it possible to view radio emitting objects at spatial resolutions that are up to thousands of times better than at optical wavelengths. Space-based VLBI will allow excellent investigations of black holes at the centres of galactic nuclei to continue. Canadian technical expertise and industry will also play an important role in international projects of this sort.

C. National Observatories

National facilities are ones operated solely by Canada. The two of concern in this report are the NRC laboratories, the DRAO, and the DAO. These facilities provide unique opportunities to train graduate students in radio and optical astronomy, to design and test new instruments, and to run unique, high quality scientific programs.

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

The CGPS is an exemplary project for its scientific impact upon our knowledge of the galactic interstellar medium, the extensive collaborative links between the NRC and universities that it has fostered, and the training of a new generation of radio astronomers in this country as witnessed by the significant number of Ph.D. theses that it has spawned. The LRPP finds enthusiastic support for the galactic plane survey from many astronomers and graduate students across the country (see Volume II, A.4).

The DRAO is also vital to our participation in ALMA as well as the SKA.

• ***The LRPP recommends*** that the two DAO 1.2 and 1.8 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.

The DAO is an essential element in the landscape of optical and infrared astronomy in Canada. The two observatory telescopes are inexpensive to operate and therefore fulfill extremely cost-effective training and instrument design roles, as does the DRAO synthesis telescope for Canadian cm radio astronomy. There is unquestionable value in using the DAO telescopes for such programs as orbits for near-Earth asteroids, stellar spectroscopy, and long term monitoring of active galactic nuclei (see Volume II, B.3).

D. People

Modern research groups at universities or institutes are most successful if they are composed of a number of people with complementary skills and at different stages in their careers. Senior scientists at either of these institutions need to have the resources to do first rank work: adequately staffed institutions, vibrant university laboratories, a good complement of excellent graduate students, accomplished post-doctoral fellows, access to competitive computer facilities and a staff dedicated to their maintenance, and to vigorous public outreach programs. Groups developing instrumentation require, in addition, high level technical and engineering support.

The LRPP finds that the ideal conditions for fostering first rate research groups are seldom met in Canada, even at our best institutions.

D.1 Institutes

The NRC and the Canadian astronomical community enjoy a deep partnership. Canadian astronomers absolutely depend upon NRC's expertise to design, build, and maintain our telescopes, instruments, and observatories. The current staff at the HIA is very thinly stretched in just maintaining our present commitments at Gemini, CFHT, JCMT, and the National observatories. Even by moving personnel from other facilities, thereby resulting in their closure and immediate loss of hard-won research capability, the current staff levels are probably insufficient to enter also into a new world facility. An additional concern is that many of the HIA's greatest experts in these fields are within 5 to 10 years of retirement.

The LRPP finds, in agreement with recent reviews of the HIA, that the staff levels at NRC's HIA are barely sufficient to maintain our present international commitments. It will be difficult to enter into new demanding projects, such as the world facilities, without substantially improving this situation. The LRPP finds this to be a common concern within the Canadian community.

•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 scientific leadership.

It is important that the highest level, international competition be held in order to attract the world's best astronomical talent to the HIA. This is essential if the Institute is to effectively carry out its challenging mandates in the coming decade. The HIA should be generously supported as a first rank institute in astronomy.

• 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.

One of the most visible international institutes in all of astronomy is the Canadian Institute for Theoretical Astrophysics (CITA). This is one of the top five astrophysics theory institutes in the world, and has made one of the most significant contributions to Canada's current high level of recognition in astronomy. It is essential that CITA continue to flourish.

The LRPP has found universal support for CITA and its mission across Canada. It has been advocated as a model for other institutes, even in other fields such as mathematics and physics. CITA has been a highly visible contributor to the national effort in astronomy through funding a CITA National Fellowship program and conferences, as well as providing support for research leaves of astronomers across Canada. It has built important links with many universities across the nation. Its strength in such fields as cosmology offer natural links with science that will flow from both CSA and ground-based astronomy programs. Support for CITA from NSERC, as well as through CSA and NRC programs, is strongly encouraged.

D.2 Universities

The LRPP underlines the profound sentiment in our community that deeper partnerships between NRC, NSERC, CSA and the universities are highly desirable. Such links foster the mission of university groups to forward basic research in astronomy and to train the next outstanding generation of talent. The LRPP finds that there is now nearly a critical inability of university groups to train the instrument builders that will be essential to promote Canadian participation in the proposed new facilities.

The LRPP identifies the virtual disappearance of university instrumentation laboratories as another potential point of critical failure in Canadian astronomy.

Cutbacks in the support of university research have drastically affected groups that construct small instruments and packages. There is not a single university laboratory left in the country that has the required personnel and financial resources to take on instrument projects at the scale that HIA can. Although in our long term plan the HIA would still be the major builder of the large instruments and facilities, the universities should rebuild their role to explore highly innovative instrument design, training, and the capacity to build small instrument components.

•***The LRPP strongly recommends*** that university laboratories for experimental astrophysics be created. This should be one of the highest priorities for moderate 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 recommends that a plan for the creation of university instrument groups (see the proposal in Volume II, G) be further developed and funded through NSERC. The sites for these centres should be in university departments and funding should be awarded through rigorous national competition. These university groups would be an ideal way of establishing closer connections with the NRC and CSA in creating widely-based expertise in the art of building front-line instruments for ground and space based observatories. Such centres should not, however, drain significant manpower or resources from NRC in particular. At least one, but no more than three such centres should be contemplated. These laboratories would create small instrument packages for optical/IR astronomy, radio astronomy, and space-based astronomy. University laboratories could also do the fundamental research on nascent technologies that is so important for the design of new instruments. They would also act as critical training grounds for talented young astronomers interested in designing and building instrumentation for ground and space-based observatories. These groups would also prepare Canadian students to enter the job market in technically-current areas. Likely centres are at universities in Quebec, Ontario, Alberta, or British Columbia.

The LRPP suggests that NSERC and CSA could provide funds for a few engineers and postdoctoral fellows to complement positions made available by the universities.

D.3 Postdoctoral Research Fellowships

It is imperative that Canada increase its investment in human resources as well as in its facilities. One obvious way of increasing the effectiveness of Canadian research groups is to make it possible for excellent Canadian scientists to employ postdoctoral fellows within their group. There are two important paths by which this can be achieved.

• ***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 prestigious new Herzberg Fellow 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 postdoc within their own groups.

The LRPP finds a strongly held community view that excellent individual Canadian scientists should be able to support postdoctoral researchers in their groups.
A prestige fellowship program is another excellent means by which highly talented postdoctoral fellows can work in Canadian university research groups. By such

highest level fellowship programs, the CSA, NSERC, and NRC will gain high visibility in the Canadian and international community. Such a program would also foster a much needed linkage between these agencies and the universities. The competition to attract the most talented individuals is severe. Therefore, it is essential that the proposed CSA/NSERC and Herzberg Fellowships be funded at a high level that is competitive in salary and research support with outstanding US institutions. Our budget provides for salaries of $50 K (Canadian) per year in 1999, but the funding level should always be kept competitive with those of the other prestigious postdoctoral fellowship competitions around the world.

The essential point is that by making it possible to attract the best young scientists in the world to do their research in Canada, we can, for relatively little expenditure, reap disproportionately large scientific returns on our facilities investments.

E. Computation

Computation is at the very heart of the way that modern telescopes are controlled; data are collected, stored and processed; and theoretical ideas are simulated and tested. Astrophysicists and astronomers have a long history of pioneering and innovative work in computation. Their knowledge has also had significant spin-offs for the information age. A good example of this is the NETSCAPE web program that was developed by computational astrophysicists at the U.S National Centre for Supercomputer Applications (NCSA) in Illinois.

The LRPP identifies the lack of adequate high performance computing resources as another of the points of potential critical failure in Canadian astronomy.

On the theoretical front, the computing capacity needed to perform simulations sophisticated enough to compare with increasingly detailed data sets is much lower in Canada than in other developed countries. The primary reason for this is the lack of sufficiently powerful mid-range parallel computers. While Canadians excel at this type of work, the actual computations need to be done on off-shore facilities, so lacking are we of the required computational power. There is wide community sentiment, as documented in the computation sub-committee study (see Volume II, D.1), that computational resources, and resource people, are at unacceptably low levels in Canada.

The LRPP urges that computational resources at many different levels must be significantly bolstered in astronomy and astrophysics in Canada. The plan addresses observational, data handling, and theory simulation needs on several levels, from the desk top to supercomputers.

• ***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.

Funding should be provided to develop innovative data mining techniques that maximize the scientific usefulness of multi-wavelength observations in astronomy (see

Volume II, D.2). The advent of very large data sets, such as optical images of 300 Mb and more in size, and observation runs that typically produce 10-50 Gb of raw data, catapult astronomy into a whole new level of computational demands. A second revolution in computation is the archiving and mining of data collected during observing runs from many different types of telescopes. The Canadian Astronomy Data Centre (CADC) at NRC, is a world leader in this field.

The NRC's CADC is developing a brilliant new approach to data bases that allows the researcher to extract information from multiple data sets in order to address astronomical problems. The LRPP also recommends that the CSA support some of these initiatives at the CADC insofar as the archiving of NGST and other space-based observatory data is concerned. The leading role that the CADC is playing in these data mining techniques could also have major spin-offs that are useful for our information based society. Furthermore, this approach helps to emphasize the notion that telescope design should incorporate data archiving as a basic functionality. In this regard, the LRPP also recommends that CADC's plan of developing such capabilities in the context of MegaPrime project at CFHT (the so-called Terapix project) be vigorously implemented.

• ***The LRPP strongly recommends*** that funds be allocated towards 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 the computational projects. Furthermore, this capability should be located at CITA to provide national high performance computing for modeling and simulations.

Ambitious numerical simulations of a host of astrophysical phenomena from supernova explosions, to star and planet formation, and outwards to issues of structure formation in the universe have become a staple of astrophysics in most developed countries. But Canada has relatively few researchers working at this level. The primary reason is a lack of high performance computing (HPC) in the country. There is only one computer available to academic users in the "Top 500'' list. Thus, computational research possibilities in this country are negligible in comparison to what is available to researchers in peer nations, a situation that must be corrected.

CITA is an ideal environment in which to build this capacity because it already has substantial expertise in computing, and has served as a focal point for the Canadian theoretical astrophysics community for nearly fifteen years. Furthermore, the LRPP recommends that support for such a facility through the NRC and NSERC as an example, would promote deep seated and highly desirable links between theoretical modeling efforts in the country and the extensive observational efforts that this plan encourages. Such possible NRC/CITA linkages would also encourage links between CITA and the CADC, to the mutual benefit of all.

It is also essential that a user support person be found who can assist astronomers across the system with the implementation of their computational research problems. This investment in skilled, knowledgeable people is very important; this role cannot and should not be taken up by graduate students or postdoctoral fellows.

• ***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 shortfall in local computer support is estimated to be a factor of up to two. The LRPP emphasizes the importance of increasing the allocations through NSERC's Equipment Grant, or comparable programs.

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

Astronomers would benefit and participate in a high level supercomputing capacity that could be made available in this way. At the very highest level of supercomputing, astronomical, and astrophysical needs can be encompassed within the national **C3.ca** consortium. The approach of building a national program from resources provided by the CFI would be of great benefit to supply a needed supercomputing capacity in Canada. Such capacity would allow the most sophisticated numerical simulations in all areas of astrophysics to be carried out on our own national facility, removing our dependence on off-shore computing resources.

F. Outreach

Healthy, long term growth of astronomy is inseparably linked with the sustained interest of the public. The public is enthusiastic about astronomy and astrophysics and new discoveries about planetary systems, black holes, and cosmology, to name just a few, resonate strongly. It is quite surprising therefore that seemingly little effort and few resources are spent in reaching out to the public in Canada. The success of NASA in bringing the HST discoveries to the attention of the American public has no counterpart in Canada. This lack of information about the importance of Canada's contribution to astronomy creates the impression that little is being done here in this field, which has the most serious consequences for the continued development and funding of astronomy in Canada. The fruits of such inattention to the public's interest in this subject are many: a level of support for astronomy that is almost a factor of five smaller per capita than in many other developed countries; the near complete absence of astronomy as a presence in government circles; the lack of easily accessible and informative Canadian web sites in astronomy for media and members of the public; and the steady loss of our brightest university students to the United States as they

seek to gain education and research opportunities at places perceived to be the generators of new astronomical breakthroughs.

• ***The LRPP strongly recommends*** that a significant portion (1.5 %) 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.

We propose that approximately 1.5% of the budget for any major international or world facility (such as ALMA, NGST, etc.) be allocated to supporting outreach efforts.

• ***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, the government, and the media. The Canadian Astronomical Society (CASCA) and the NRC, should create a state-of-the-art astronomical web site. This should be one of the highest priorities among the outreach initiatives.

It is vital that a Canadian astronomy web site be established through collaboration between CASCA, the NRC, with the participation of CSA as well. This site should provide any interested person with abundant information about astronomy both in the international context, and the discoveries that Canadians have contributed as well. It should provide current information about activities at all observatories and facilities at which Canadians are making contributions. The LRPP also recommends that announcements of recent discoveries be made on a regular basis to a wide list of interested educational institutions, amateur astronomy groups, and members of the media.

• ***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 web site, and establishing a budget that could support an information officer who could co-ordinate these activities.

The appreciation for astronomy and science is most effectively begun well in advance of high-school. Given that the future of astronomy lies with the continued interest and talents of young people, CASCA must have a visible presence in the fabric of science education in our schools. By giving children a feeling for real astronomy and the excitement of discovery, we will be also contributing to the overall appreciation of science in general. This is crucial if Canada is to play a leading role in this age of exploding scientific frontiers and information driven, techno-logical culture.

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

This program provides deserving undergraduates with the opportunity to obtain first hand experience in astronomical and astrophysical research. These students often go on to graduate school as a consequence of this background.

3. Summary of Priorities

The plan outlines initiatives of vastly different types and financial commitment. Accordingly, we summarize the priorities for Canadian astronomy for these different categories. There are two levels of priority for projects within each category and no ranking is implied for projects within a level. **The LRPP wishes to be absolutely clear that second priority projects should definitely be funded; second priority does not imply second rate science or level of impact.** Rather, the first priority is a rating that we give to projects that have unique capabilities, that we could not drop without doing severe damage to Canada's future in astronomy, and that also emerged with consistently high support across all sectors of our community.

• MAJOR NEW FACILITIES

1. The highest priority in Canadian astronomy is our participation in both new, first generation, world observatories; ALMA and NGST.

2. The WF8m and the FIRST/PLANCK mission are very important facilities. Canada's positioning of itself now for future entry into the SKA and VLOT second generation world observatories is very important.

• MODERATE SIZE FACILITIES AND PROJECTS

1. The highest priorities are the LAR PHASE B studies; the VLOT design study; the enhancement of correlator and receiver groups, and continued commitment to the Gemini project.

2. The support of JCMT until 2009; the Canadian Galactic Plane Survey until 2005; and the CFH 3.6 metre telescope until the appropriate time (after 2006) during the ramp-up of a WF8m project, are all important commitments. Canada should invest in MegaPrime and WIRCAM for the CFHT. The enhanced operation of the DAO telescopes is an important program.

• INSTITUTES

1. The highest priority is to increase the permanent astronomy staff by at least 6 additional positions at NRC's HIA in order to support its instrumentation, facility design and operation efforts; as well as to significantly strengthen its prominence in scientific research and leadership. There should also be a top-level, Herzberg Fellowship program.

2. The support of CITA as one of the world's leading research institutions is very important.

• UNIVERSITIES

1. The highest priorities are for the creation of university laboratories for experimental astrophysics as well as a top-level NSERC/CSA Fellowship program.

2. The support of university research through increased individual operating grants, opportunities to hire postdocs, and NSERC grants to summer and graduate students are all important programs.

• COMPUTATION

1. The highest priority is for the continued development of the CADC and the establishment of a mid-range computing capability for theoretical and computational astrophysics.

2. The participation of the astronomy community in a national HPC network and increased levels of NSERC support through Equipment Grants are important programs.

• OUTREACH

1. The highest priorities are the creation of a national CASCA/NRC web site; as well as the expenditure of approximately 1.5 % of project funds upon outreach programs to the public and the media.

2. The leadership role of CASCA in educational outreach to schools and teachers is an important program.

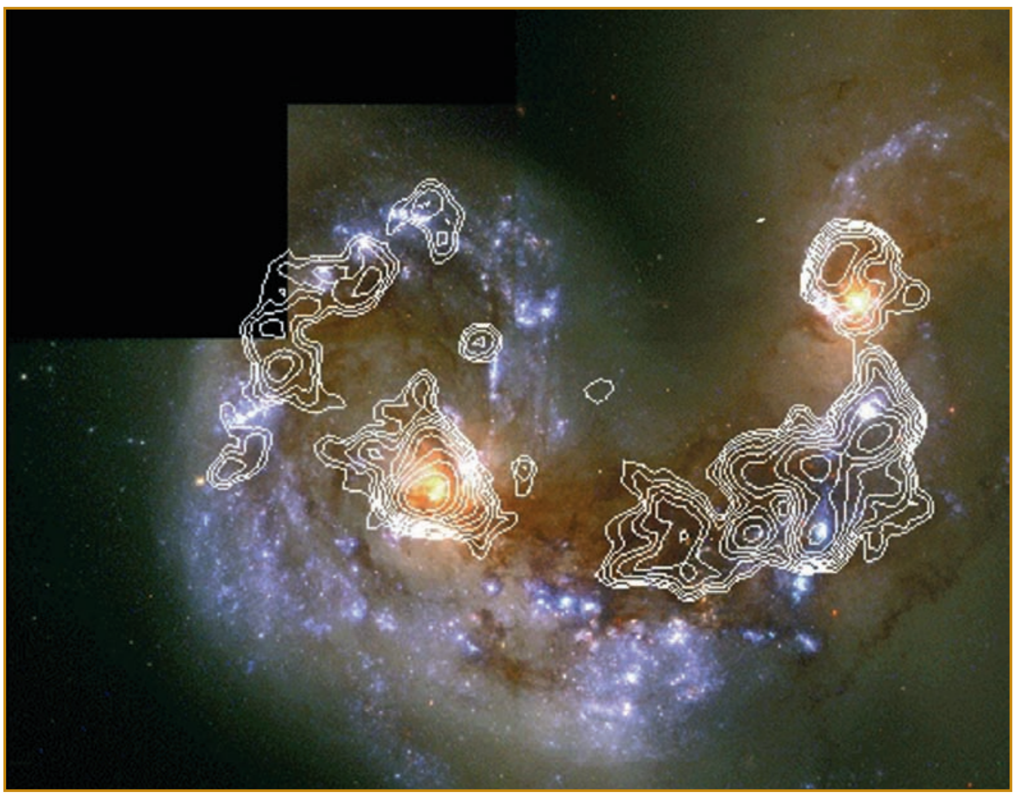
4. Budget

• Table 1 summarizes the projects and recommended expenditures in the NRC budget over the next decade for astronomy and astrophysics in Canada. Items with the highest priority are indexed with a star. The total 10 year additional expenditure of $ 147 million is not frivolous; we will have a very large return to Canadian science, culture, and the economy as we shall describe.

• ***The LRPP strongly recommends*** that the CSA invest $ 50 million US over the next decade in the NGST project in order to secure the maximum possible scientific and technological impact. The CSA should also allocate funds for involvement in the FIRST/Planck satelleite. We also recommend that the CSA invest in the CADC data analysis initiatives as well as support half of the recommended, high profile, CSA/NSERC Fellowship program. We estimate that these total expenditures reach 100 million dollars (Canadian) over the next decade.

• ***The LRPP strongly recommends*** that NSERC support the proposed university centres for experimental astrophysics. The costs of postdoctoral and technical support amount to 350 K per year per centre. Thus the funding of at least two centres requires approximately 7 million dollars over the next decade. NSERC should also support half of the recommended CSA/NSERC Fellowships program, for a total of nearly 2 million dollars over the decade. NSERC should double its equipment grant pool through an increase of nearly 5 million dollars over the next decade. Finally, NSERC should raise the individual operating grants of excellent scientists enabling them to support postdoctoral researchers; we propose that an increase of 3 Million over the next decade could sustain this. We therefore argue that NSERC should increase its funding for astronomy over the next decade by approximately 17 million dollars.

• ***The total recommended investment*** of all three agencies would help to lessen the gap between Canada and its industrial partners in terms of dollars per capita spent on astronomy and astrophysics. The direct leverage factor of the plan of approximately a factor of 2 (see Chapter 8) on this investment could yield a return of at least a half billion dollars to the Canadian economy. The indirect benefits in the form of high tech spin-offs to Canadian industry and technology are much greater.



A colliding pair of spiral galaxies called the Antennae is seen here with the radio emission contour lines that show areas of molecular gas superimposed on the HST optical image.

Courtesy Christine Wilson, McMaster University

CHAPTER 6

Computational Impact of the Plan

Astronomy can be regarded as consisting of three overlapping areas of expertise: observational, theoretical, and computational. Astronomers have always been leaders in exploiting the capabilities of the newest computational tools. Computational power is necessary for observation and data analysis while numerical modelling is the experimental arm of astrophysics. It is indispensible for developing and testing advanced, realistic models of every kind of astrophysical system: planets, stars, galaxies, and cosmologies.

In this chapter we emphasize the fundamental role of computation in the plan, and its impact upon astronomy as well as science and technology in general. We draw upon the thorough study carried out by our computation subcommittee (see Volume II, D.1).

6.1 Computation: the Current Situation

Virtually all data now arrive from astronomical instruments and detectors in electronic form. Thus the recording of images and spectra, their manipulation and analysis, and all forms of modern data archiving, are completely dependent on computing. Observational astronomers have been major users of computer hardware, and major users and developers of software for image processing, spectral analysis, and instrument development and control.

In theoretical astronomy, computer use ranges from the numerical solution of mathematical equations to the simulation of complex physical phenomena. Numerical simulation codes can follow the orbits of planetary systems over billions of years; the evolution of dilute plasmas in stars and the interstellar and intergalactic media; and the evolution of the dark and gaseous matter in the early universe that assembles to produce galaxies and cosmological large scale structure.

Canadians have demonstrated a particular strength in the development of astronomical software, ranging from observational data-reduction packages to large-scale simulation programs. The world's premier software package for the reduction of stellar photometric data was developed, and is maintained, at NRC's Dominion Astrophysical Observatory. Similarly, NRC's Canadian Astronomy Data Centre (CADC) is an international leader in providing innovative solutions for theprocessing and archiving of astronomical data, and for "data mining"through creative linking of databases. In theoretical astrophysics, a number of the leading simulation codes were developed by Canadians (though in all cases but one, the work was performed outside Canada). These latter include the numerical codes used to simulate the astrophysical jets in galactic nuclei and regions of star formation, and the process of star formation itself. Three of the four widely used cosmological particle codes and a leading Lagrangian hydrodynamics code were written by Canadians.

The LRPP emphasizes, through its recommendations, the need for serious and enduring commitment to the implementation of an effective computational environment in Canada. Such an environment will ultimately benefit many scientific and technological areas, not just astronomy.

We identify four major computational needs:

1. Handling of large data volumes:

Just one year's worth of observation at any of the new telescopes now generates many terabytes of data. Furthermore, proprietary and archiving policies make the data publicly accessible conventionally within a year or two of their acquisition, so that the entire community can benefit from, and contribute to, the analysis and modelling or use them for projects unimagined by the original investigators. Effective management of such large data volumes requires adequate archiving facilities, powerful local processing capabilities, and access to high-bandwidth networks.

2. High performance computing:

The lack of a nationally available, multidisciplinary, high performance computing program in Canada has been a severe impediment to both our academic and technological competitiveness. While the federally supported, Canadian Foundation for Innovation (CFI) has recently provided some much needed funding for a few computational initiatives (eg. PSciNet at the University of Toronto as just one example), the problem is still acute. For Canadian astronomy, which has access to world-class observational facilities that are producing data of unprecedented scope and detail, the lack of depth in computing capability is a serious limitation. It is increasingly true that the superb new observational data produced by these facilities can only be fully exploited in conjunction with substantial modelling and simulation programs. At present such investigations must be pursued outside Canada.

3. User support:

Large-scale computation requires committed user support, including help in the use of parallel computers, visualization, and efficient access to data archives. Without this support, it is much more difficult to grow a community of users who will take full advantage of the rich observational databases and drive substantive theoretical progress.

4. Maintaining adequate hardware:

Today, computing hardware is both relatively cheap and rapidly becomes obsolete. Just as for ancillary instrumentation on telescopes, computers must continually be replaced so that research which is computationally intensive may remain competitive. With redeployments necessary every 2 or 3 years, **computing hardware is more appropriately viewed as an ongoing research cost instead of infrastructure.** Computer hardware is improving so rapidly that upgrades are essential to remain competitive.

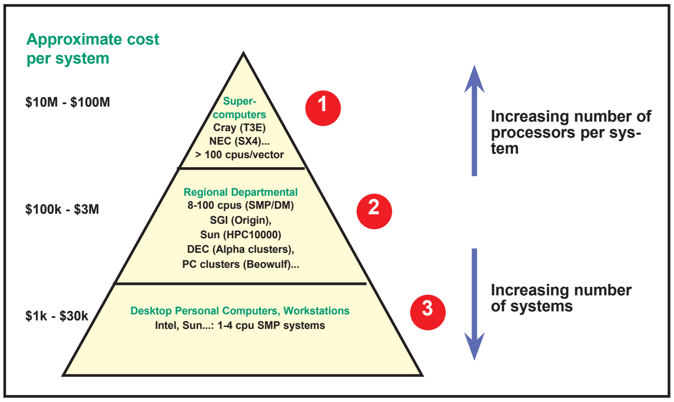
These requirements are common to most computationally intensive communities. The response has been the development of a three-level pyramid of computing capability. The base of this computational pyramid is the realm of desktop systems, and the peak is the supercomputer. The properties of the machines at these different levels are easily summarized:

Level 1: The supercomputers are a combination of Massively Parallel Processors (MPP) or large vector/parallel systems and typically reside in nationally supported entres. The centres provide programmer and application support and development. The cost per machine is in the range $10 M - $100 M and they may contain 100 or more CPUs. Examples are the Cray T3E, and the NEC SX4.

Level 2: The intermediate level consists of machines ranging from perhaps 4 to 64 processors and are either shared memory processors (e.g., the Origin 2000 or Sun Enterprise systems), or are distributed- memory clusters of workstations. Such systems are located regionally or may be local collaborations within a university or even a single department. These machines typically cost $100 K - $3 M.

Level 3: Desktop systems are typically single or dual processor PCs or workstations. Their typical cost is in the range $1 K - $30 K.

The demand for level 1 computer cycles in astronomy relative to other fields can be gauged by the fractional use of computer cycles at the U.S. National Centre for Supercomputer Applications (NCSA). The demand is approximately 20%. Similar demands of between 10 % and 20 % are found at supercomputer sites in the U.K. and Germany.



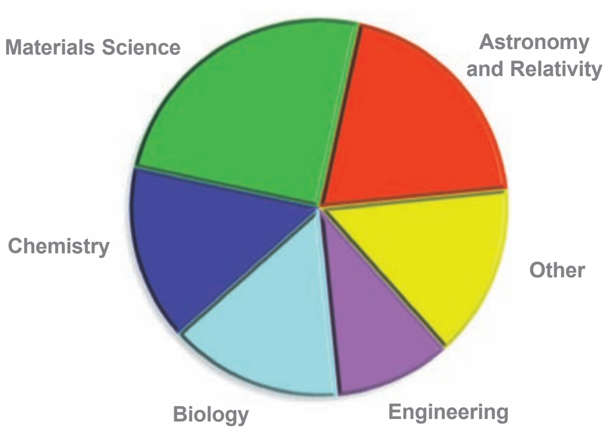
The pyramid of computing capability.

Courtesy Hugh Couchman (McMaster University)

It has been well documented that Canada lags, very significantly, most industrialised countries in hardware for high performance computing. One computer available to academic users makes the ``Top 500'' list. Powerful systems are available within some sectors. Canada has seven systems appearing in the November 1998 Top 500 list: four at Bell Canada or BCTel centres and one each at Sobeys and the Toronto Stock Exchange. The other system, an NEC SX-4 at the Atmospheric Environment Service, Dorval, would on its own place Canada 6th in the accompanying chart, between Sweden and France. The systems represented in the chart have overwhelmingly been financed through national programs, such as the National Science Foundation in the U.S. The contrast between these machines and those available to support national academic computing within Canada is glaring, all the more so when it is realized that innovation in computing often begins in academic research programs.

The fact that level 1 computation is not strongly represented in Canada, except in industry and the weather service, has serious consequences especially for numerically oriented theoretical research in astrophysics. Its absence stifles theoretical research in all of the areas reviewed in this report. This gap translates into a noticable deficit in the number of researchers who undertake large-scale computations in Canada - the number is estimated to be less than ten - far less than the critical mass of people required to create a truly competitive international presence in this field.

This situation also has a noticable effect upon the hiring of new faculty in our universities. The relative absence of this highest level of computational skill in our leading institutions has the additional consequence of denying training in numerical techniques and their application to understanding complex data sets. In many cases students who wish to pursue their graduate work in this field must turn to much better computationally supported institutions in the U.S. and elsewhere. This lack of skilled people in a critically important area affects not only astronomy, but our larger scientific and technological society as well.

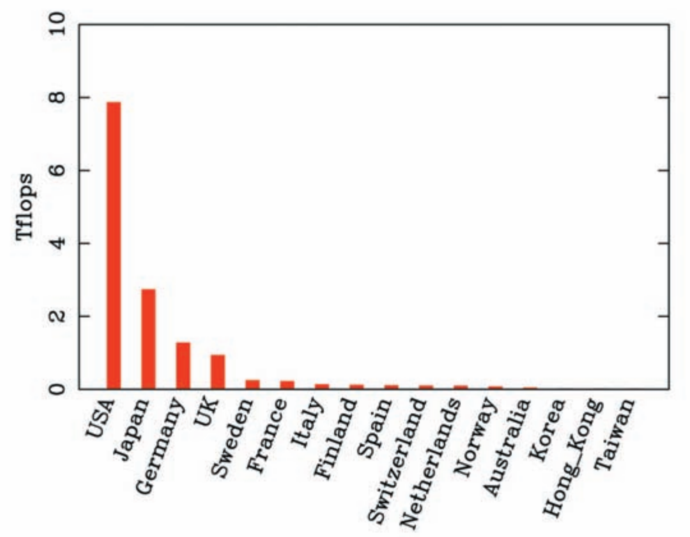


Computing cycle usage at the USA National Center for Supercomputing Applications (Illinois), separated by discipline. Astronomers and astrophysicists are heavy users of high performance computing.

Courtesy Hugh Couchman (McMaster University)

The lack of a full complement of the necessary computational facilities is felt at level 2 as well. Theoretical astrophysicists in Canada have access, until the present time, to an 8 processor, SGI Origin machine at CITA. While the recent CFI initiatives are helping, it is sobering to realize that level 2 capacity is now rather common to find (up to 64 processor machines) at the departmental level in the univerisities of other nations (eg. Princeton, Oxford). Academic researchers at CITA and the University of Toronto will have access to a NEC SX5, which is roughly 12/20 the aggregate power of the Dorval SX4. The general lack of such mid-level machines, necessary for many simulation programs, could be overcome by the relatively modest investments recommended in this plan.

Finally, the situation at level 3 - desktop computing - can be maintained at an effective level if the level of support given to NSERC equipment grants could be increased by a factor of two.



Total high performance computing capacity available to academic users by country. Data plotted are derived from the November 1998 "Top 500" computers list and show the aggregate power for each country of all computers available to academic users. Using these criteria, Canada has one machine devoted to academic computation in the Top 500.

Courtesy Hugh Couchman (McMaster University)

6.2 Computation: Recommendations and Impact

Our plan is designed to redress four important concerns within computation over the coming decade.

(a) A highest priority in observationally related computation is that the CADC be given the necessary resources to host archives from the new observatories as well as to develop innovative data mining techniques. For some image processing tasks, datasets are pushing the limits of what is possible on single-CPU computers. CADC and DRAO are beginning to investigate the use of cost effective clusters of PCs as powerful HPC solutions for the processing of large astronomical images. The knowledge gained will be invaluable to the wider astronomical community which will inevitably have to face many of the same problems when reducing data at local institutions. The CADC can play a pivotal role in leading the investigation and development of these techniques and the LRPP urges that adequate funds be made available for this purpose.

(b) The highest priority in the area of theoretical computation is to secure a level 2 capability for our community. This can be achieved most effectively by capitalizing on the existence of the highly successful and modest HPC consortia that are already centred at CITA. The LRPP recommends that funding should be used to:

• provide a user support person. An NRC-funded person at CITA helping the theoretical HPC community could provide an effective bridge with the CADC efforts. This will create exciting new links between our community, NRC (through CADC), and CITA.

• provide a timely upgrade which would buy the astronomy community - in a formal and concrete way - access to the CITA machine. The upgrade of the Origin 2000 is a possibility as is the purchase of an additional processor for the SX5.

The support and upgrade of the mid-level parallel computer there, coupled with the funding of a local user support person, is an excellent way of fostering an international presence in high performance computing. Such a facility would help to seed ambitious new efforts in large scale simulation in fields such as planet and star formation, as well as galaxy formation and cosmology.

This facility would also provide a unique and exciting means of creating a deep partnership between the NRC and CITA. The need for a support person is also emphasized. It will be important for most potential users in our community to be able to tap the expertise of a person skilled in parallel computing and other advanced techniques. The proposed linkage of NRC and CITA in this way bears many similarities to the proposed centres for experimental astrophysics with CITA playing the role of host institution. High speed networking will also play an important role in such an enterprise if it is to work effectively as a national resource for theoretical computation.

(c) The need to create a broad, multi-disciplinary, national high performance computing capability is also strongly supported by astronomers. The decision to attempt a degree of national coordination via the **C3.ca** consortium is a welcome recognition that Canada needs a national HPC program.

The CFI program is for five years of funding. It is imperative that strong representations should be made, beginning immediately, to national funding agencies for continuing financial commitment to HPC beyond this window.

Care must also be taken in trying to construct a national program from the resources to be funded by CFI. The computing hardware being proposed is at level 2 of the pyramid and the issue of sharing the limited resources must be carefully handled. Achieving equitable access for excellent researchers with significant HPC needs is a difficult task. The question of providing user support must also be addressed.

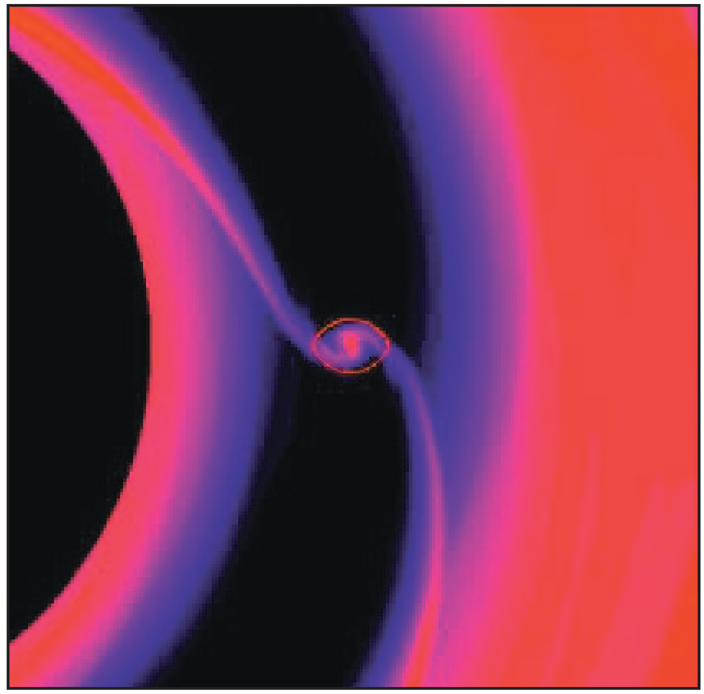
(d) At level 3, the one which affects virtually every member of our research community on a daily basis, we recommend that NSERC provide additional support for desktop computing through its Equipment Grant program.

These recommendations will provide Canadian astronomers and astrophysicists with the computational tools needed to fully exploit the output of our new facilities.

6.3 Impact upon Theoretical Astrophysics; Towards New Frontiers

The ultimate goal of all of our efforts is to gain a deeper insight into how structure appears and evolves in the universe (see Volume II, E). It will be the new ideas and fresh conceptions of the universe that emerge from our efforts that will be their greatest legacy. These new ideas will need to be tested in the laboratory that is provided by sophisticated numerical modelling.

Among the greatest breakthroughs in our understanding in the coming two decades will be in the realms of star and planet formation. There is currently no general theory available for how stars aquire their mass, yet this simple distribution affects many areas of astrophysics. Major progress in this field depends upon the development of new algorithms that will enable the researcher to study the formation of protostars within self-gravitating, turbulent, magnetized, and highly clumpy gas within molecular clouds. This capacity together with the data that will flow from the next generations of instruments will transform this field. In the next decade or two we should have a theory of star formation that is as precise and successful as our present theory of stellar structure and evolution. Two decades from now, we will also likely have sufficient data about other planetary systems to spur an authoritative theory of planet formation which can take into account the amazing variety of planetary systems that we are now just beginning to uncover. Such a theory will be the necessary first step toward accurately predicting the conditions that lead to the formation of terrestrial planets capable of sustaining life.



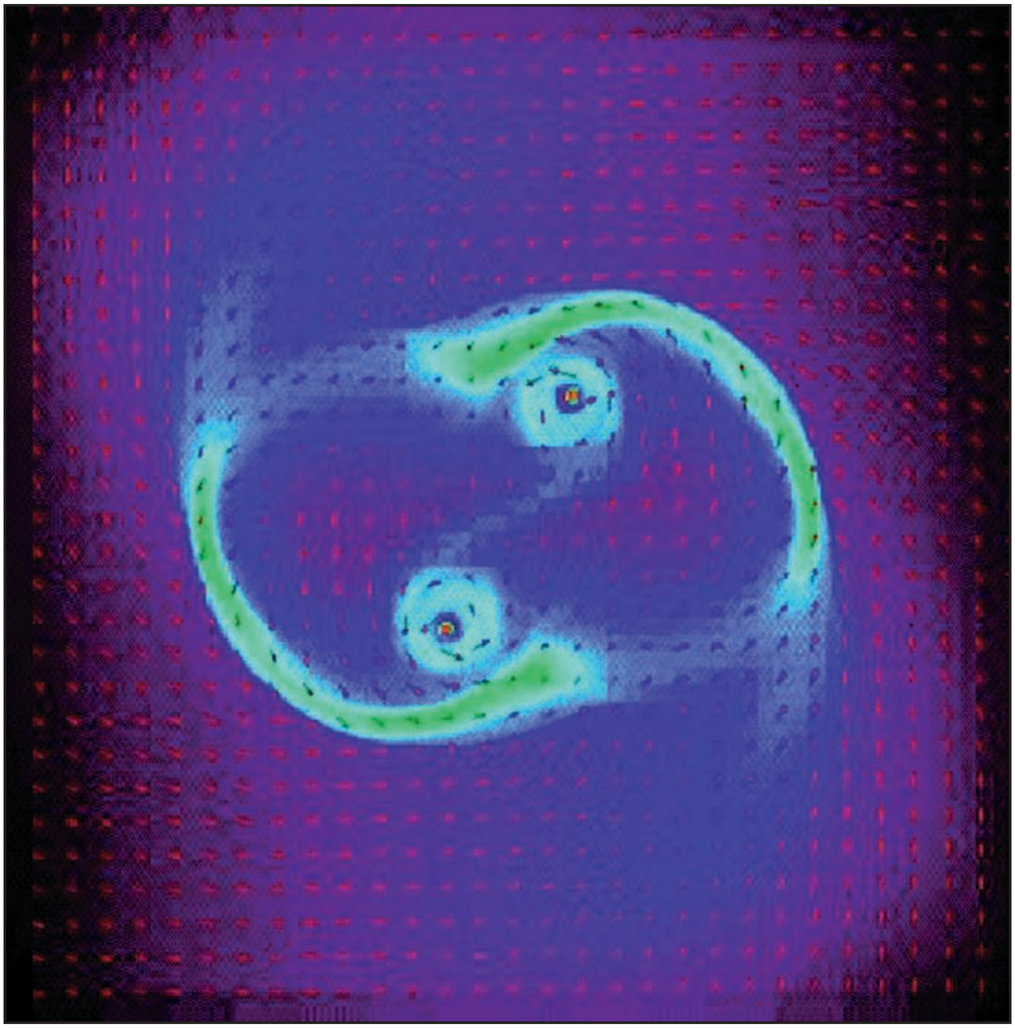
A 2-D simulation of the formation of a Jupiter-sized planet from a planetary disk, seen here face on. Note the accreting streams of gas falling onto the proto-planet and the gap which has been cleared in the disk.

Beuzit et al., 1997. ESO

Our current understanding of galaxy formation was greatly advanced by the detailed numerical simulations that cosmologists perform of the growth of density fluctuations in the early universe. These computations and simulations have laid the foundations for a sophisticated understanding of galaxy formation that is testable by current observational programs. The results, so far, broadly support the simulations, giving credence to the underlying theoretical idea of how structure grows in cosmology. Here too revolutions in thought may be awaiting us. The amount of dark matter in the universe will certainly be more precisely determined in the coming decades. This knowledge will directly impact theories of galaxy formation and on the largest scales, the evolution of the universe.

Perhaps the most tantalizing prospect of all is that we will gain a better understanding of whether or not the universe underwent an inflationary epoch in its earliest moments. Good evidence for this will no doubt play a central role in the history of astronomy and physics. Once again, the main tests of these ideas will likely involve the confrontation of detailed numerical simulations of the basic physical ideas with the data.

Finally, the conditions in the early universe when it was small enough to be governed by quantum mechanics as well as by gravity, are the ultimate laboratory for particle physics. The deepest challenge in physics is to elucidate the link



A 3-D adaptive mesh-refinement (AMR) simulation of the formation of a binary from an initially rotating cloud. The stars, each with a surrounding disk, the circumbinary disk and inflowing materials are visible. Simulations like these are necessary to understand and test competing theories of star formation. Klein et al., 1998. AMR codes will be a crucial part of these efforts. Simulation run on a Cray C90, Pittsburgh.

between quantum mechanics and gravity and to combine these into a single concept. Currently popular ideas suggest that the fundamental particles of matter – best likened to vibrating strings – could be the means by which this synthesis is realized. String theory is highly "non-linear" so that here too, numerical simulation may ultimately play a decisive part in testing the viability of this next revolution in physics. Thus, the computational aspects of astronomy and astrophysics will play an ever growing and more important part in our quest.

C H A P T E R 7

Cultural and Educational Impact of the Plan

The health of a culture and economy in the information age depends on its ability to contribute to basic research, to compete technologically with other nations, and to educate its citizens both in science and the arts. The pursuit of astronomy and astrophysics furthers all of these goals. We examine the impact that the plan will have upon important educational and cultural issues.

... in learning science you learn to handle by trial and error, to develop a spirit of invention and free inquiry which is of tremendous value far beyond science. One learns to ask oneself 'Is there a better way to do it?'

Richard P. Feynman, American Nobel Laureate in Physics

7.1 Signatures of Public Impact

Among all the sciences, astronomy has the unique power to reveal the true scope of the outside world. This immense and enduring appeal of astronomy to the public allows it to act as a powerful "science magnet":

• Almost one million people annually visit Canadian observatories and planetaria. As just one example, more than 25,000 people visited the Observatoire du Mont Megantic "Astrolab" in its first year, despite its remote location in the Eastern Townships. This thriving center now includes a small telescope specifically for visitors, and has contributed strongly to the public awareness of astronomy (and science) in Quebec. Well attended visitor centre programs are maintained at several other observatory sites around the country. For most people, simply looking through a telescope at Saturn or the Pleiades may be the most memorable direct experience of science that they will have in their lifetimes.

• At the elementary school level, teachers know that the two scientific topics guaranteed to excite their students are dinosaurs and outer space. At the university level, approximately 10,000 Canadian students elect to take non-specialist courses in astronomy each year; for most of them, it will be the only formal university contact they will have with science. The lecturers in these courses know from long experience that a palpable hush falls over the class whenever topics such as black holes, the search for other planets, Earth-crossing asteroids, or the origin and fate of the universe are brought up.

• A rough indicator of the public impact of science is reflected in the numbers of sites present on the WorldWideWeb. Biology, with its huge personnel base, leads all scientific disciplines with almost 12,000 web sites. Astronomy ranks second with 2300 sites, ahead of chemistry, physics, mathematics, or earth sciences. Special events attract enormous Internet followings: for example, the Mars Pathfinder landing in 1997 generated roughly 700 million "hits", 43 million of them on a single day; and there are several authoritative web sites devoted solely to information on the planets around nearby stars. The web sites operated by the Space Telescope Science Institute Office of Public Outreach now experience 20 million hits per month and rising, and have active referrals from 23,000 other web sites around the world.

Interest in the sciences can be stimulated at a very young age.

Photo courtesy Stephen Barnes, Burlington, Ontario

• In the wide-readership science magazines such as Scientific American and Discover (and even including the science features in news-magazines such as Time, Newsweek, and MacLeans), articles on astronomy and space science appear in far higher proportion than for any other science: these disciplines represent about 7% of the science features, though they have fewer than 1% of the active scientists. Television programs such as @discovery.ca present frequent features on astronomy that are very popular.

• Astronomy, among all sciences, has the highest relative participation by non-professionals. In Canada, 22 cities have chapters of the Royal Astronomical Society, a highly networked and active organization of amateur astronomers. Its membership is ten times that of CASCA and represents an excellent intermediary between the professional astronomer and the interested public.

7.2 Astronomy and "Spaceship Earth"

Astronomical discoveries are extraordinarily effective at making us realize that the Earth is very directly affected by events in the universe around us:

• Gradual changes in the energy output of the Sun, and alterations in the sunspot cycle, translate directly into climate changes on the Earth. For example, the "Little Ice Age" that chilled Europe for an entire human lifetime (from 1645 to 1715) was the result of a shutdown in the normal sunspot cycle.

• Techniques developed through astronomy and space science have been used to monitor ozone depletion and global climate change; to model planetary atmospheres as a baseline for comparison with the Earth's atmosphere; and to track continental drift by the radio astronomy technique of very long-baseline interferometry.

Comet Hyakutake cuts an elegant path across the night sky during its 1996 passage by the Sun. The icy, dusty nuclei of comets may be the only remaining pieces of the original "solar nebula" from which the planets were built.

Photo courtesy Stephen Barnes (Burlington, Ontario)

• Flares on the Sun send out a "solar wind" of high-energy particles and radiation that impact the Earth's magnetic field. These events create brilliant aurorae but can also interfere with terrestrial radar and communication networks, sometimes causing severe power grid outages at unpredictable times. A good example is the massive solar storm that resulted in the 1988 Hydro Quebec outage that left most of the province without power for hours. That event was predicted by the NRC/HIA solar patrol, but ignored.

Spaceship Earth, from the historic Apollo 11 Mission

Courtesy NASA

• The Earth is bombarded continually by small objects in the solar system including meteorites, comets, and asteroids. Though the tiniest of these (chunks of rock and ice a few meters in size down to dust grains) have little effect, a collision of a big comet or asteroid many kilometers in size would be devastating to Earth's biosphere. The gravitational tugging of Jupiter upon the asteroid belt appears to be responsible for producing a steady supply of Near-Earth Asteroids (ones whose orbits cross the Earth's, and may therefore eventually get swept up by the Earth). Although the annual probability of a truly catastrophic collision with one of these is small, a more complete understanding of these objects could quite literally save human civilization.

7.3 Astronomy as a Driver of Basic Science

Astronomy has had by far the longest history of influence of any branch of science. The ancient Greek philosophers developed the first genuinely scientific system of thought partly in order to understand the regular but extraordinarily complex motions of the planets. In the 1600's, the revolutionary discoveries made by Galileo with the newly invented telescope, and by Kepler with mathematical laws of planetary motion, demonstrated the true nature of the solar system once and for all. The "Newtonian synthesis" which followed a century later included the invention of calculus, the law of gravity, and the birth of modern physics and engineering. All of this was stimulated by the drive to understand the motions of the Moon, planets, and comets in a complete system of the cosmos.

During the 20th century, astronomy and astrophysics generated an astonishing string of discoveries which have constantly pushed the frontiers of science. In the early part of the century, the clinching evidence for Einstein's new theory of general relativity came from two astronomical phenomena (the orbital shift of Mercury and the bending of starlight passing near the Sun). Quantum mechanics found unexpected and powerful verifications in the rate of energy generation from the Sun, and in the structures of ultra-dense objects like white dwarfs and neutron stars. Particle physics has been strongly influenced by the solar neutrino experiments. In more recent years, the truly extreme conditions represented by the first microseconds of the Big Bang currently demarcate the ultimate frontiers of physics.

7.4 Public Outreach Initiatives

Public interest in astronomy is essentially universal. Astronomers therefore have a unique opportunity to inform the public and to enhance its enjoyment and appreciation of science and knowledge in general. This benefits both the public and the long term health of astronomy and scientific endeavour in general.

Public nights at observatories attract visitors all through the year.

KPNO / NOAO / AURA

The responsibility for an excellent public outreach effort rests with both individual astronomers and our agencies (NRC, CSA, and NSERC). The direct contact of the astronomer with the public, media, educators, and members of the government must be matched by sustained outreach efforts in the agencies to elucidate how funded research efforts lead to new knowledge and technological innovations.

Our plan argues for several ways of achieving this complementary approach: by on-site visitor centres at our major observatories; by knowledgeable news reports in the media; by authoritative information through attractive and well designed website; by regular contact with the government ministries; and by enhanced educational outreach in the schools.

All of these areas need major work and should be done as a cooperative effort among CASCA and the three major funding agencies for Canadian astronomy: NRC, NSERC, and CSA.

(a) Within HIA, the DRAO center should be modernized, and a new center at DAO should be located separate from the Plaskett Telescope dome. These steps will help the public to gain direct experience of what an observatory actually looks like and how it is run.

(b) Astronomy needs a physical presence in Ottawa and on Parliament Hill. To this end, a new visitor centre should be created at the most appropriate NRC site in Ottawa. The fine science being done within NRC deserves much increased visibility in a place where it will have the most direct educational and political impact. NRC should consider hiring a consultant to develop a strong outreach plan and an expert whose role will be to maintain and continually improve centres.

Astronomy-based news items are almost always exciting and positive, but far too few of these media reports use Canadian sources or inform our taxpayers what their supporting dollars are achieving. The LRPP plan emphasizes that CASCA and the funding agencies have major new roles to play here as well.

(c) Close ties must be developed with media journalists across the country. It is important that CASCA and NRC be pro-active in getting authoritative information about astronomical discoveries out to the media, regularly.

(d) CASCA should build much closer connections with our enthusiastic amateur astronomy organizations across the nation. Amateur groups help to bring the excitement of science to the public first-hand.

(e) CASCA should strongly encourage its members to communicate their results more frequently and more effectively – from public talks in their local communities and schools, to contact with their Members of Parliament, to Breakfast Seminars in Ottawa.

(f) Lastly, we recommend urgently that CASCA and NRC with participation of CSA develop a first-rank web site for astronomy that emphasizes Canadian roles, successes, and aspirations. The enormously successful web sites operated in the USA by the Space Telescope Science Institute, by the National Optical Astronomical Observatories, and by the divisions of NASA, are superb models of this type of public outreach: they demonstrate the full power of astronomical images to convey, instantly and around the world, excitement about the science as well as serious information. The construction and maintainence of a site of the highest quality and with distinctive Canadian content, will require the constant attention of professionals.

Taken together, these efforts should help to foster among our citizens the deep sense of excitement, of informed scientific inquiry, and of the many opportunities that astronomical exploration and its new technologies present to us all.

7.5 Outreach in the Schools

Contact with the domain of education is the most underdeveloped aspect of our public outreach. Students and their teachers have to be reached at every level of education, from elementary to graduate school. Each level demands a different type of involvement.

Our recommendation that CASCA play a decisive, enlarged role in this field implies a broadened mandate for its Education Committee (see Volume II, F). It must become a task force. Step by step, relationships must be forged between professional astronomers and teachers in the elementary and secondary schools. The programs sponsored in the USA by the Astronomical Society of the Pacific (ASP) as well as the National Optical Astronomical Observatory, the American Astronomical Society (AAS) and NASA , provide several excellent models for these initiatives. Workshops for science teachers promote the exchange of teaching methods, demonstrations, and tools; these take place occasionally in Canada, but need to be incorporated into our educational culture. CASCA should help promote and organize these in every province every year. Teacher/astronomer "pairings" would take this exchange even further.

As a pedagogical tool for science, astronomy can be used for illustrative purposes for a variety of goals and thus integrated into many different topics (this is the approach adopted recently in Quebec). Most important is continuity: educators and professional astronomers must be reliably and consistently linked together.
The national web site, a regular newsletter, and regular meetings, should all be used to communicate recent discoveries, arrange workshops and site visits, and develop ties with planetaria and museums.

At the university level the impact is different. Campuses that teach the ever popular, introductory astronomy courses will need to modernize their lecture halls to implement web site contents and interactive demonstrations. Finally, at the graduate student level, our future scientists should involve themselves in the activities listed above. This can be done through better teaching assistant training and direct contact with younger students in the schools.

Implementing all these initiatives will need commitment and money but is utterly necessary for the future health of not only astronomy, but of our inquiry-based, scientific culture in general. Within CASCA, a developmental fund needs to be defined for this purpose, along with a permanent Information Officer. CASCA, through such an information office, should also seek further funding opportunities for these programs, perhaps through educational foundations and other private and government programs.

At the agency level (NRC, NSERC, CSA), all major projects supported by them (CFHT, JCMT, Gemini, and the new international initiatives outlined above) should have distinct budget items for public outreach, designed to describe and promote their scientific results. All these efforts should be centrally co-ordinated through a joint effort by CASCA, NRC, and CSA. How much should public outreach efforts cost? Comparison with the most effective outreach efforts in the USA (Space Telescope Science Institute, NASA, and the national observatories) suggests to us that 1.5% of any agency budget should be specifically allocated to public outreach. This investment is both modest and cost-effective: it will be repaid manyfold by the long-lasting positive effects on the public perceptions of science, and the role of science in the schools. Within HIA, this percentage would translate into a permanent Outreach Office with about three staff members.

CHAPTER 8

Economic Impact of the Plan

The links between "pure" research programs in astronomy and their economic impact have always been substantial and are often surprising. The construction and operation of the new world observatories, however, will take this activity to new levels. These projects are of such a scale that close working links between astronomy and industry will be absolutely central. In this chapter, we present several of the many outstanding examples of how astronomy drives new technology and creates important new opportunities for industry. Most of the examples listed below are Canadian-based ones, but many more can be drawn from the American and European communities. We then discuss the substantial economic impact of our global plan for Canadian astronomy. Our economics analysis also draws upon an independent consultant study, commissioned for the LRPP (see Volume II, H).

In the most advanced countries, government investment is directed first and foremost towards the development of education, science, and culture. Every crown the state invests in those fields will return to it a thousandfold, though the profit cannot be measured by standard accounting proce-dures.

Vaclav Havel, 1991, Prime Minister of the Czech Republic and playwright

8.1 Strong Partnership Between Astronomy and Industry: an Example

A superb illustration of the economic potential lying within the link among astronomy, technology, and industry is the story of AGRA-Coast (Port Coquitlam, BC). In the late 1970's, this firm gained a $4M contract to build the dome for the CFHT on Mauna Kea. Their traditional road and bridge work benefitted directly from their successful attack on construction problems at high altitude and freezing temperatures, and the direction of the company changed toward one of advanced technology that now includes design and simulation, satellite tracking, and sophisticated theme-park rides among other applications. The company is now the world's leading builder of enclosures for large telescopes: it has constructed the domes for the Keck I and II optical telescopes; the Japanese Subaru telescope; the Gemini North telescope (all on Mauna Kea); Gemini South; and two UK optical telescopes on the Canary Islands. AGRA-coast has also built radio antennae for the Owens Valley (Caltech) mm array.

The AGRA-Coast contracts for the Gemini project alone are valued at $44M, which should be compared with Canada's original $38M capital investment to enter Gemini (generated by combined contributions from NRC, NSERC, and the WESTAR Corporation). The firm’s work on all telescopes since the 1970's has now grossed $150M. The overall effect is larger when it is realized that the firm is now a knowledge-based one with annual contracts above $10M/yr. AGRA-Coast has subcontracted many parts of its telescope enclosure work to smaller firms in the Vancouver area, stimulating the technology businesses there.

8.2 Spin-offs: Astronomy as a Stimulus to Economic Growth

The stimulation of economic activity generated from the construction and operation of major astronomical facilities is not restricted to only dome and telescope construction. The spin-offs reach very far into the structure of the economy:

The Gemini North dome at an early stage of construction.

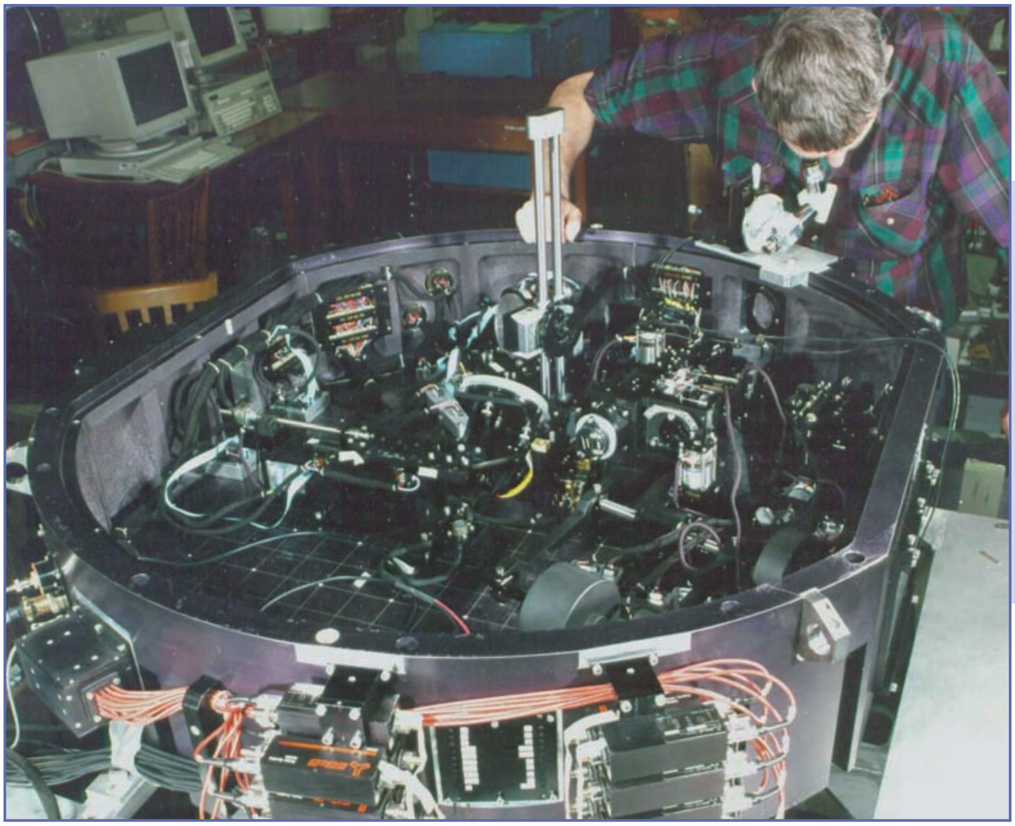
Courtesy AURA / NOAO / NSF

• Smaller Gemini contracts have been let to a variety of other BC companies including Ramsay Engineering, Stevested Engineering, and ASA. About 80 Canadian firms expressed written interest in the Gemini work at preliminary stages, indicating the range of possible economic opportunities. The HIA itself was awarded contracts worth approximately $8M for sophisticated instrumentation.

• An earlier concrete example of industrial spinoff came from the Toronto-based firm DSMA Atcon Ltd., who in the mid-1960's invested $0.25M in a design for a 4 metre class optical telescope. The design work enabled them later to bid successfully for numerous components of telescope projects in Italy, Germany, and Australia, as well as nuclear research and space robotics projects. The leverage factor of its initial astronomy involvement was estimated by the company President to be 40 to 1.

• Canada's enormously successful RADARSAT employed cleverly implemented, aperture synthesis for coherent signals, a technique developed by radio astronomers for imaging the sky.

• The Centre for Research in Earth and Space Technology (CRESTech, one of the Ontario Centers of Excellence), in collaboration with HIA, CSA, and NRCan, developed a version of a data acquisition and recording system in the so-called S2 format for the purpose of correlating Very Long Baseline Interferometry (VLBI) data from radio telescopes. CRESTech has made sales of approximately five dozen S2 recorder, formatter, and playback systems to about a dozen countries including the USA, Japan, Australia, India, and France with revenues of about $6M to date, equal to the S2 development costs. Sales are continuing, and its association with the DRAO data correlator facility, which is the most advanced in the world, is an added strength. A former CRESTech employee used the S2 project as a springboard to form a new



Modern instrumentation for astronomical telescopes requires a combination of advanced optics, electronics, computer control, and compact construction. An optical instrument for the Gemini telescopes is shown here in the HIA laboratories.

Photo courtesy HIA / NRC

spinoff firm Datavation; it sells a terabyte-scale data storage system and is expected to generate revenues on a similar scale.

• The Institut National d'Optique (INO, Ste.Foy, Quebec) carries out extensive research and development in photonics, optics, electro-optics, and lasers (annual operations $18M), and has performed extensive astronomy-related work for CSA, the European Space Agency, and other contractors. They employ several astronomy-trained staff and their work includes laser range scanners, optical amplifiers, fibre optics, active, segmented, and diffractive optics. Its mission is to provide R&D assistance to high-technology companies, and their expertise would match many areas of the Long Term Plan.

• Two students from École Polytechnique started a small company, Matrox, in 1979 to produce electronic cards for storing numerical images at the Mont Mégantic Observatory (OMM). Today Matrox is a world leader and has export sales in excess of $200M annually.

• In 1984, two researchers at OMM (the director and a student) developed a digital system for computer display of astronomical images. The student subsequently went on to found the software company Softimage. This firm has grown into a world industry leader in professional visual content production, with tools for creating 3-D and 2-D animation, as well as creating, editing and finishing video programs.

• The University of Alberta's Department of Electrical and Computer Engineering, in collaboration with HIA and the Alberta Microelectronic Centre (now the stand-alone Alberta Microelectronic Corporation, or AMC), led to the development of prototype antenna/receiver modules using state -of-the-art superconducting-insulator-superconducting (SIS) technology. This is of use in astronomy, but also industry (through AMC) for use in various mm- and sub-mm engineering projects and other cryogenic SIS projects, for which AMC now has fabrication capability.

• The University of Lethbridge is currently involved in a project to rapidly measure the amount of water vapour along a given path through the atmosphere for phase correction of radio interferometer data. This may lead to a method of rapidly determining air density variations at airport runways, having the potential to be a powerful diagnostic tool for airline pilots, with an important safety angle. A second example is the gold coated nickel metal meshes which were developed for a spectrometer launched on the Infrared Space Observatory (an ESA mission). The university was part of a team that tested the optical performance of these meshes. Later these meshes were found to be ideal surfaces for rapidly growing skin for severe burn victims whose skin must be replaced within a critical period. The meshes have been used at major US burns institutes.

• At the University of Victoria, recent research on the time ephemeris of the Earth has refined (by roughly two orders of magnitude) the relationship between Earth-based and solar-system based clocks. This has implications for solar system spacecraft ranging.

• Queen's University has developed algebraic computing methods that have been used in the financial industry, and it has provided computing consulting to the industry.

• The University of Waterloo's astronomical imaging techniques have been used in medical imaging and remote earth sensing research.

• York University spun out Stellar Optics Research International Corporation, which markets products and consulting in the area of black and white materials and surfaces. This company now supplies flat fielding screens to astronomers worldwide, and got its start as a result of two contracts, one related to providing advice on materials or surfaces suitable for flat field astronomy CCD images; and the other for advice on black surfaces suitable for the baffle of the Far-Ultraviolet Spectroscopic Explorer (FUSE). In addition, York astronomers have learned how to make ultra-precise spheres which will be used for the new international density standard, and astronomical software has been transferred to the private sector for applications in research and education.

• At CITA, faculty have been involved in developing microwave detectors for use on satellites. Although a theory institute (so direct applications are not generally in their line of work), some post-doctoral fellows have earned income providing images and animations of galaxy mergers to the entertainment industry.

• The American decadal review of astronomy and astrophysics published by the National Academy of Sciences in 1991 lists at least a dozen other major applications of astronomical techniques in other areas of industry. These include image processing software in automobile and aircraft labs; communication antenna testing; low-noise components for communications industry; development of highly sensitive photographic films by Kodak; infrared-sensitive films for aerial reconnaisance; and X-ray baggage scanners for airports.

8.3 Spin-offs: Some of HIA's Contributions

NRC policies encourage entrepreneurship and assistance to Canadian industry. Among many commercially related activities in the past three years, HIA staff have:

• Helped a small company develop a cell phone antenna that is more energy-efficient and directs less radio emission into the user's head.

• Developed an elegant new lens coating technique, applied to patent it, and have begun discussions with businesses for its widespread commercial potential.

• Organized and offered a "virtual antenna" test facility available to private industry.

• Worked closely with COMDEV (Cambridge, ON) on several technical support issues for satellite instrumentation, notably the fine error sensors for NASA’s recently launched FUSE spacecraft supported in part by CSA.

• Provided technical assistance to Bristol Aerospace on its LIDAR (space) te• Worked with NRC's national library, CISTI, and the University of Victoria Mechanical Engineering department to establish a database of fuel cell R&D

HIA is actively engaged in a number of other projects that are potentially of great future interest to both industry and government users. These include optical astronomy projects (including those for the NGST), radio wavelength technologies, and data processing technologies.

Strategic HIA technologies

Optical Technologies	Possible Applications
Aspheric optical components	Advanced optical systems for a broad range of applications
Optical coatings	Optical systems of all kinds
Visible light and infrared detectors	Extremely sensitive imaging detectors
Adaptive optics	Ophthalmology, remote sensing, any application involving poor seeing conditions
Control systems	Very wide application to all kinds of problems
Space -qualified hardware development	Space programs in the widest sense
Structures and enclosures for large optical telescopes: applications	Large and expanding international astronomy markets

Radio Technologies (e.g., ALMA & SKA)	Possible Applications
Control of flexible structures	Robotics
Low-cost innovative actuator design	Many applications possible
High-performance array antennas	Telecommunications satellite antennas
Tethered robotic vehicle controls	Undersea vehicles, stabilized airborne platforms
Precision photogrammetry and advanced metrology for large structures	Fabrication and precision measurement of extremely large structures and machinery, precision machine control
High-precision GPS-based geomatics	Precision surveying
Cryogenics	Low-cost cryocoolers for mass application in computers and telecommunications. High-performance cryogenics for semiconductor industry and scientific research equipment.
High-temperature superconducting technologies	Telecommunications filters and satellite components
Precision structural design	Other astronomy facilities, antenna design, satellite antennas
Carbon fibre and other advanced materials	Many applications, including ultra-stable structures, satellites
Generation of high power at hundreds of GHz	Telecommunications, research equipment
Semiconductor material processing	Semiconductor industry, high-performance sensors
GHz digital device design	Computing and digital systems at the high speed frontier, signal processing, telecommunications
High -performance digital filters	Telecommunications, signal processing

Data Processing Technologies	Possible Applications
Techniques of large databases of images and other information applications	Libraries, statistical data, all kinds of scientific, medical, environmental, financial and technical data, relational and other database expertise, Internet access to databases, development of archives (especially for remote retrieval), multimedia archives, permanent storage management software, pipeline processing
Image processing techniques	Engineering, medical imaging
Parallel processing technologies	All kinds of computationally intensive data problems, parallel complier technology

8.4 Applications to Medicine and Medical Research

One of the strongest directions of application is in medicine and medical science. This spinoff area is not as surprising as it might seem at first, since medical diagnosis relies heavily on imaging (X-ray, ultrasound, and so forth), and many of the principles used in imaging analysis involve finding faint "signals" in the presence of all kinds of "noise", exactly what astronomers are trained to do. Image reconstruction techniques from radio astronomy have been put to use for CAT scans, magnetic resonance imaging, and positron emission tomography. Microwave receivers have been employed in scans for breast cancer. Astronomical image processing software has been applied to angiograms and monitoring neuron activity in the brain. A recent review of the IAC (Instituto de Astrofisica de Canarias, a Spanish and European consortium and one of the largest observatories in the world) lists approximately 20 instances of their consultation or applications to medicine over the past decade.

Some of the most recent medical applications are striking indeed. Researchers in two American universities are developing an adaptive optics system drawn from infrared astronomy into a method for imaging the retina of the human eye in living subjects at unprecedentedly high resolution. At the IAC, engineering staff have collaborated with a neighboring university medical laboratory to develop a prototype device which may eventually allow blind people to "see", through what is called Virtual Acoustic Space: miniaturized digital cameras worn like a headset over the subject's eyes feed optical images into computer-correlation software and are transformed into a stereo sound signal which is fed back to the user's ears, and can be interpreted as a picture of the space ahead.

8.5 Training Impacts

Astronomy and astrophysics graduates go on to positions in academia, observatories, the private sector, government, and other occupations, taking their expertise with them. Some stay in Canada, others move abroad.

There are several studies which trace where graduates of astronomy departments find employment. Each has a somewhat different methodology, but the results are reasonably consistent and are summarized in the table below. The most recent survey of Canadian university astronomy departments (see Volume II, H) shows that about half their graduates remain in Canada, at least in their first position. Data from the HIA are very similar. These figures are lower than the roughly 80% average of NSERC postgraduate award holders who remain in Canada [1], but it represents the reality that many, if not most, astronomy positions are at international observatories sited outside the country. It is likely that many individuals who move abroad will eventually return to Canada, bringing additional experience and expertise with them. We do not have direct evidence of this for astronomy graduates, but nearly half of former NSERC post-doctoral fellowship holders who held their awards abroad intended to return to Canada for employment[2] , and it is probably reasonable to expect a roughly similar proportion for astronomy professionals.

Although roughly half of graduates remaining in Canada take up academic posts, the other half enter non-academic positions in industry and government. Thus there is a substantial transfer of astronomy-derived expertise to the private sector and (to a lesser extent) government from university departments.

PERCENTAGE OF ASTRONOMY GRADUATES GOING TO:

	Academia & observatories	Industry	Government	Other	Don't know
Canadian university survey done for the LRPP (1999), graduate students, post-docs*,					
In Canada (54% of total)	23%	20%	2%	8%	2%
Abroad (46% of total)	31%	2%	2%	8%	2%
Overall (100%)	54%	22%	4%	16%	4%
Data from HIA (1999), graduate students, post-docs, and RAs:					
In Canada (47% of total)	31%	14%	1%	1%	4%
Abroad (53% of total)	44%	6%	3%	–	–
Overall (100%)	75%	20%	4%	1%	–
CASCA Ph.D.s (1996)	42%	27%		30%	–
Australian survey of Ph.D.s from US, Canada, Australia, Holland (1999)	45%	35% non-astronomy		20%	–

**Data from 13 of 19 relevant departments*

[1]Postgraduate Survey - 1994 NSERC. March 1995, p 14.
[2]Final Report Evaluation of the Scholarships and Fellowships Programs of the Natural Sciences and Engineering Research Council. The ARA Consulting Group (now KPMG Consulting LP). March 1993

8.6 Benefits and Costs of Astronomy and Astrophysics

It seems entirely justified to anticipate a 40% annual rate of return, and a total benefit to cost ratio in the neighborhood of 2.0 (see details in independent economic study given in Volume II, H). Both figures are calculated on the basis of gross industrial revenues compared to the joint investment of government and industry combined (ie. including industry commercialization and production costs). Canadian gross industrial revenues can quite reasonably be expected to be 10 times the government research investment alone, and could well be higher if one or more firms become very successful at exploiting construction or instrumentation applications. These figures represent only the easily-identifiable benefits, and even then only those that can be quantified in dollar terms. We would confidently expect many other non-quantifiable-but nonetheless very real-social, medical, environmental, training, innovation systems, and other benefits as well. The economic impact study shows that it is important to support a substantial number of projects and potential applications from which “big winners” can emerge, and to engage in active technology transfer. In the absence of such conditions, the investment may not be nearly so fruitful.

Our overall conclusion is that a vigorous astronomical community generates an atmosphere of creativity and economic activity that stimulates a huge cross section of society.

8.7 Economic Potential of the Long Range Plan

The economic benefit of the Long Range Plan, detailed in Chapter 5, falls into two categories. First is the direct financial gain from contracts won by Canadian firms for the construction and operation phases of each project. We estimate, rather conservatively, that this direct economic return to the country is at least 2 to 1 over the lifetime of each project listed below.

Second is the "spinoff" stimulus to a wide range of high-technology businesses, generated as the new concepts in each project find their way into many other technological avenues across Canada. The leverage factors in this area are considerably harder to predict and to document. They depend more sensitively on the entrepreneurship of the high technology community within Canada in a more general sense, as well as on the ability of NRC/HIA to find and make the right connections for applications in industry. But the examples discussed above suggest to us (again, conservatively) that 10-to-1 ratios in the creation of wealth are not unrealistic.

What do each of the major sections of the Long Term Plan have in store?

1. ALMA: In radio and millimetre astronomy, the most attractive instrumental expertise within Canada is its world-leading correlator technology residing within HIA. Many correlator devices will need to be built, first for the second-stage Very Large Array in New Mexico (NRAO), and then for the giant ALMA itself, later in the decade. Another industrial connection is Quantum Technologies in Whistler, B.C. who stand to gain from the development and construction of cryogenic systems for sub-mm receivers. The delivery of the huge number of receivers that will be required to equip ALMA will provide excellent large contracts for high-tech companies. Canada is an attractive partner for its ability to design and build these components which have large potential revenues. Yet another very large opportunity lies in the fabrication of the radio dishes and supporting structures that will be needed for the array. Canadian firms such as AGRA-Coast have already indicated an interest in competing for their construction.

Expected direct economic return: $100M over one decade

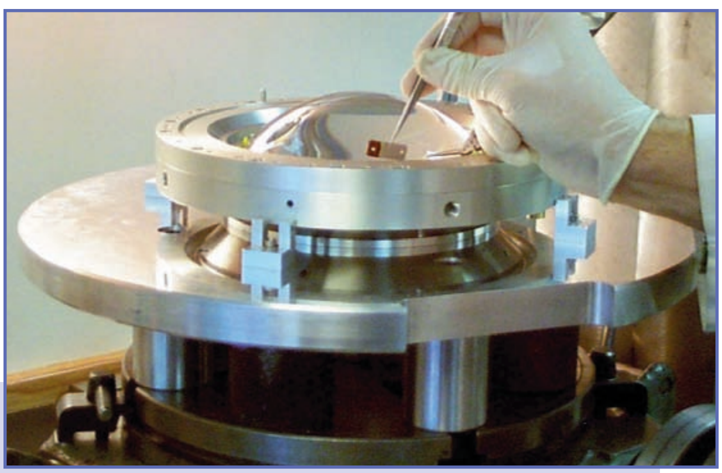
2. NGST: Canadian participation in this major CSA-sponsored project will have exciting consequences for our aerospace industry and many high-tech firms.
The CSA is currently funding studies of two "spacecraft" areas including communications, involving EMS Canada (Ste. Anne Bellevue, Quebec), and structures, through the involvement of Dynacon in Toronto. There are three current Canadian initiatives underway for the scientific instruments on NGST (imagers and spectrometers). These projects are being pursued with industrial partners such as EMS (Ottawa), and the Quebec- based Bomem (a world leader in the construction of Imaging Fourier Tranform Spectrometers). For both NGST and

FIRST/Planck, expenditures will be for work in kind contracted out in Canadian firms and labs.

3. FIRST/Planck: Two examples of studies being considered by CSA are the telescope structure and testing for the Planck mission, and a high performance frequency synthesizer for the FIRST mission. Opportunities will also exist for bidding on computing packages required for the Planck mission data.

Expected direct economic return (combined NGST and FIRST/Planck): $200M

4. CLAR and SKA: Canada presently has one of the two leading prototype designs for the Square Kilometre Array, the next major step in decimetre radio astronomy. If the Canadian aerostat design proves feasible through prototype construction and ends up as the competitively selected technology, it will yield an enormous payoff in both scientific impact and economic spinoff. Many possibilities in correlator and receiver design offer excellent industrial opportunities. The LAR aerostat concept for the antennas in the array also features large reflectors which could be constructed by experienced Canadian companies. The aerostat concept may lead into major spinoff areas which would employ inexpensive large-aperture antennas for applications such as deep space communications and radars.



Astronomical instruments require exquisitely designed optics and electronic control.

Photo courtesy HIA / NRC

Expected direct economic return: $30M over the next decade; considerably more in the following decade if the Canadian LAR concept proves to be the selected design for the full-scale observatory

5. VLOT: The next generation(s) of optical/ infrared ground-based telescopes will rely heavily on innovative designs for combinations of wide-field and high-resolution imaging, for which Canadians have unexcelled experience. Constructing an optical/infrared telescope in the size range of 25 metre or larger will involve steps upward into new technologies in lightweight materials, computer control of large structures, optics, camera and spectrograph design. Opportunities in all these areas will exist particularly if Canadians are partners from an early stage.

Expected direct economic return: $50-100M if our national share of a VLOT is similar to that intended for ALMA and NGST.

6. Gemini: Canadian involvement in the construction of the twin 8 metre telescopes has already more than repaid the capital investment made to join this project. A key instrument under construction by the Herzberg Institute staff is the adaptive optics "front end" which will deliver superb images to the cameras and spectrographs. Over the next decade, roughly a dozen new Gemini instruments will be coming on line as part of the first and second generation instrument plan, typically with costs in the $3-5 M range each. Canadian labs can reasonably expect to acquire the equivalent of two of these if they maintain current standards of technical capability.

Expected direct economic return: $5M over the next decade, added to the $53M already garnered since the beginning of the project

7. WF8m: The rapid deployment of a WF8m is possible because we have already been engaged in the Gemini 8 metre project. It is anticipated that the substantial economic return that has already been derived from Gemini would be repeated for a WF8m effort, particularly since Canada should have a larger share of this telescope than in Gemini.

Expected direct economic return: $80M over the next decade

8. Information Technology: The management and distribution of information is playing an increasingly important role in all areas of science, technology, and business. **The Internet, and its associated tools such as Netscape and HTML (which were invented by an astrophysicist and a particle physicist), have generated nothing less than a revolution in society and business.** Information handling, data handling, and software development are areas in which Canadian astronomers have considerable expertise. In particular, the data mining concepts being pioneered at HIA/CADC promise to have enormous impact. The principle of correlating databases with efficient high-level tools will become a powerful approach in industry, engineering, library management, and virtually all branches of physical and social sciences.

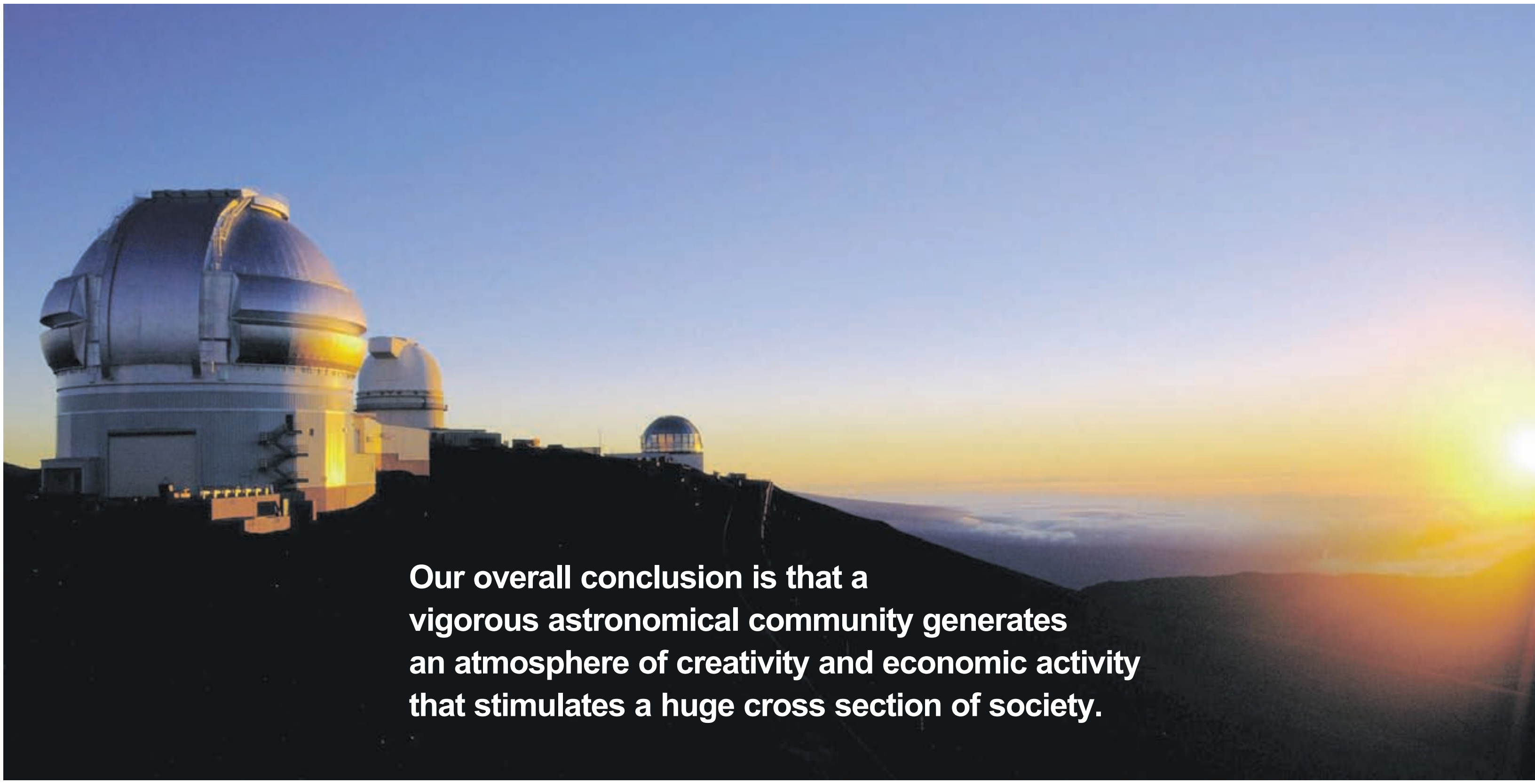
The newly completed Gemini North 8 metre telescope on Mauna Kea, at it's 1999 commissioning.

Courtesy Gemini / NOAO / AURA

Canadian industry is very interested in the opportunities that arise in the high technology and engineering, as well as in the fabrication of the telescopes and other components of this plan. It is telling in this regard, that 24 Canadian firms signed a recent letter of interest in support of a proposal to NSERC for an astronomy-based, National Centre of Excellence.

In sum, we anticipate that the direct economic impact on high-technology business within Canada will be to produce business exceeding $450M - $750M over the next decade. The broader stimulus to many areas of technology should be much larger, at least 10 times the government's annual investment. It would therefore be injurious not to harness our business and technical acumen in this era of astronomical exploration. The benefits will accrue to Canadians in the plethora of ways that this report has discussed. The returns to the economy are well documented and well understood in other countries that have invested in their technological base in this way. Their societies are reaping the resulting benefits that Canada has, so far, largely ignored.

We conclude this study with a reaffirmation of its basic vision. The exploration of the universe is our human destiny. What we propose in this plan, to explore the origins of structure in the universe with new tools and a renewed investment in skilled people, will provide our descendents with the necessary foundations for this inescapable quest. It will provide us with the confidence, exhilaration, and technological and cultural renaissance that comes from bold and timeless adventure.



Our overall conclusion is that a vigorous astronomical community generates an atmosphere of creativity and economic activity that stimulates a huge cross section of society.