The Status and Future of General/Space/Atmospheric Physics and General Relativity in Canada

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Executive Summary

The purpose of this document is to provide an overview of the fields of physics covered by the NSERC Grant Selection Committees (GSC's) 17 (atmospheric physics and space science) and 29 (general physics), evaluate their strengths and weaknesses, make recommendations on the suitability of NSERC funding, and formulate a vision statement for the future. Included in the terms of reference is a consideration of risk-taking and spin-off activities, and the role of present and future inderdisciplinary initiatives. The results are based on responses to a questionnaire circulated to all members of the respective communities in August, 1996, together with a supplementary analysis of the research programs supported by NSERC.

General physics is defined to be all areas of physics not covered by subatomic physics (GSC-19), condensed matter physics (GSC-28), or atmospheric physics, astrophysics, space science, and gravity research (GSC-17). The main areas included are atomic and molecular physics, laser physics and optics, plasma physics, statistical physics, and mathematical physics, together with various applications to areas such as medical physics, photonics, surface science, atmospheric physics and astrophysics. At first sight, one might think that this would lead to a loose collection of topics that is lacking in focus. A primary conclusion of this study is that in fact these topics are closely woven together by common threads of both underlying theory and experimental technique. The diversity of the field results from the wide applicability of these common underlying elements. The diversity represents a strength in that researchers can quickly respond to new opportunities as they arise. From diversity comes fluid adaptability. The single most important unifying theme is "lasers and their many varied applications."

A new opportunity now does indeed present itself. The present Canadian strengths in the above named areas of general physics are well-rooted in the early Canadian excellence in optics and spectroscopy. Consequently the Canadian physics community was well positioned to take advantage of the new possibilities provided by lasers. Their rapid development from the 1960's onward has constantly revitalized the field as new regimes of intensity and frequency control become accessible. Canada has established a strong presence in the design of lasers and their applications to spectroscopy, surface physics, photonics, plasma physics, aeronomy, fibre optics, nonlinear phenomena, and communications. To take just one example, the applications of optical fibres to new surgical techniques, telecommunications and the INTERNET have revolutionized our lives. Several high-tech companies in Canada have been spun off from university-based research as a result of these successes. We are now at the threshold of even more dramatic advances in the areas of ultrahigh intensity, ultrashort pulses and ultrashort wavelengths (x-ray lasers). The impact of these advances will be broadly interdisciplinary, with applications to chemistry, biology and medicine, as well as to the traditional areas of physics. A new initiative in laser science and spectroscopy would also involve strong participation from condensed matter physics since many laser systems are solid state, and many laser interactions with matter involve surfaces and solids. It is important for Canada to capitalize on these opportunities by building upon the existing strengths in laser science, spectroscopy and atomic physics, as well as in condensed matter physics.

All plasma physics and plasma technology development programs would reap enormous benefits from advances in laser science. Laser diagnostics provides an essential tool for studying plasmas ranging from magnetic-confinement fusion tokamak plasmas (still active in Canada) to plasma reactor discharge plasmas. Lasers also play a key role in creating or modifying plasmas in plasma reactors or other plasma-based devices, such as those used for x-ray laser development. In addition, lasers provide one of the most important means for determining the rates of atomic and molecular processes required in the modelling of plasmas. Finally, many other plasma applications such as the plasma processing of surfaces are limited by the available average powers and repetition rates

of lasers (see Sect. 5.3, p. 31).

In atmospheric physics, Canada has a strong international reputation for the study of atmospheric processes such as the aurora and ozone depletion. A particularly important Canadian contribution is the use of lasers for atmospheric sounding (lidar), resulting in the highly successful Optech Company (see Sect. 10.2, p. 72) and its world leadership in lidar technology. This technology is limited by the current capabilities of lasers, and would benefit directly from future improvements. As with plasma physics, lasers play a key role in the determination of the rates of basic atomic and molecular processes required for atmospheric modelling.

Many of Canada's best theorists are in the area of general relativity and gravitation, and Canada has a strong international presence here. Although this area has traditionally been dominated by theorists, one of the most exciting prospects now coming onto the horizon is the possibility of detecting gravitational radiation produced during the collapse of black holes etc. Here also laser improvements play a role because the sensitivity of gravity wave detectors (of the Michelson interferometer type) is limited in part by the laser power available (see Sect. 11.4, p. 83).

In view of the above, the first recommendation is:

> **Recommendation 1a.** (see Sect. 11.1, p. 78) A new initiative in laser science and spectroscopy, and its many varied applications, would be broadly beneficial to Canadian Physics, and to other disciplines such as Chemistry, Biology, and Medicine. It would build on existing strengths, and it would have an excellent potential for economic spin-offs. However, additional funding is required in order to make significant progress in a strongly competitive field.

It has been well stated that AMO (atomic, molecular and optical) science is a powerful enabling science. As such it undergirds and supports many other areas of science, engineering, technology, and applications. Thus, in addition to producing world-transformational devices such as the laser, it also produces the foundational knowledge of atomic properties and interactions which are necessary for the development of a host of other areas. Because of this, a nation's investment in AMO science yields substantial economic benefits. A recent (1994) report of the National Research Council (U.S.) concluded that such science, through its applications to manufacturing, information technology and communications, semiconductors, and other industrial sectors, was an important enabling factor in industries accounting for about 9% of the GNP.

Canadian scientists have long been recognized as world leaders in in this field with key developments at centres such as Laval, Windsor, UBC and Sherbrooke. A wealth of cross section and other data has been produced for scientific and industrial use. In view of the above the second recommendation is:

> **Recommendation 1b.** Canada must continue to promote research that promises new technologies through the invention and development of better techniques and instrumentation to control and manipulate atoms, molecules and light for a broad range of applications, and for furthering studies of interactions at the atomic and molecular level. As with Recommendation 1a, this recommendation would build on existing strengths and would have excellent potential for economic spin-offs.

Major Collaborative Efforts across Discipline Boundaries. (see Sect. 20, p. 105) The following areas have been identified as having excellent opportunities for interdisciplinary research:

- Physics with biology, including medical diagnostics, and broader problems involving modelling the environment.

- Laser and plasma physics with condensed matter physics in the rapidly developing fields of material science and photonics. This also involves collaborations with engineers in telecommunications.
- Atmospheric physics and astrophysics are strongly interdisciplinary by nature, and rapidly becoming more so as applications to environmental studies become more important.
- Nonlinear dynamics and chaos in connection with dissipative systems. The fundamental principles have broad application across many disciplines.

All of the above involve strong interactions with mathematics through the theory of integrable and partially integrable nonlinear systems, and through the interplay between integrable systems and pure mathematics (combinatorics, algebraic geometry, etc.).

These interactions are growing stronger than ever, and are essential if more fundamental studies are to realize their potential for broader applications. The second and fourth items also confirm that there already exists a firm foundation for subdisciplinary collaboration between GSC's 28 and 29 in a laser science initiative, as described in Sect. 11.1 (p. 78).

However, a broad consensus of the community indicates that new targeted NSERC programs are not needed to encourage these developments. The researchers themselves are the best people to see new opportunities for applications in other areas. Various interactions are constantly evolving at a vigorous pace, but it is counterproductive to try and legislate them into existence through new defined NSERC programs. Other ways to encourage interdisciplinary research are discussed in Sect. 19 (p. 103). Enhanced funding should be provided through the existing program of operating grants.

> **Recommendation 2.** A major collaborative effort across subdiscipline boundaries should be encouraged by providing funding for a laser science and spectroscopy initiative, and related theoretical support, through the existing operating grant structure.

Vision for the Future. The report concludes with a Vision statement for each of the areas General Physics, Atmospheric Physics and Space Science, and General Relativity and Gravitation (Sect. 23, p. 115). The following paragraphs outline how the support of these areas is of benefit to Canada.

Benefits to Canada

We address here the question "Why is General Physics (GSC-29) and Atmospheric/Space Physics (including General Relativity) (GSC-17) of benefit to Canada?" The answers help to draw together the arguments made in the report on many different levels.

As this section is being written, the Toronto Stock Exchange has just celebrated its last day of floor trading. Henceforth, all stock transactions will be executed through computer terminals. This is just one illustration of the profound impact that computer technology and high speed communications via fibre optics is having on our daily lives. However, we have only seen the beginning of an ongoing revolution. These advances ultimately rely on our ability to measure things, whether it is the precise placement of atoms on the surface of a computer chip, or the extraction of information from a high-speed data stream.

These advances did not occur in isolation. They required many years of basic scientific discovery and development involving lasers, fibre optics, signal processing, and the processing of surfaces by lasers, plasmas, and other means. In many cases, the technological applications did not become apparent until after the basic science had been done. We now stand on the threshold of even more profound advances through our ability to control and manipulate atoms and light and their interactions. The ultimate applications of recent breakthroughs such as Bose-Einstein condensation and atom lasers can now be only dimly seen, but they will certainly be important for both basic science and engineering. The study of nonlinear phenomena in the interaction of lasers with optical materials and plasmas continues to yield unexpected suprises and novel applications in the processing of optical signals. Related fields such as opto-electronics for the design of new electronic devices, and biophotonics for the diagnosis and treatment of diseases are rapidly expanding. The pace of development elsewhere in the world is quickening in all areas of AMO science.

Until now, Canadian work on lasers, laser-atom interactions and interactions with optical materials has led the way into the information age. Our university researchers are heavily involved with major companies such as Nortel, Quebec Telephone, NBTel, Lumonics (laser manufacture), JDS Fitel (optical components manufacture), and many others listed in Table 14 (p. 94) and Sect. 10.2 (p. 72). These companies are also major employers of our students, and direct supporters of university-based research. For example, Nortel has recently established a Telecommunications Institute at the University of Toronto with $8 million in funding over the next five years. Similar industrial collaborations exist at many other universities.

However, as detailed in Sect. 21 (p. 109), the level of NSERC funding for the research supported by GSC-29 has now dropped to the critical point where research groups can no longer remain competitive with the forefront research being done elsewhere in the world. At present, there is virtually no Canadian work being done in the rapidly emerging areas such as quantum computing or Bose-Einstein condensation, and relatively little on the development of improved laser systems for faster pulses and higher peak powers. The entire research base to supply basic atomic and molecular data, and to make use of improved laser capabilities for fundamental studies and interdisciplinary applications, is being seriously eroded. In order to address these problems, we have proposed a new initiative in laser physics and its many varied applications. In our view, additional funding for this initiative is essential if Canadian industry is to continue reaping the benefits of industrial spin-offs, and Canadian students are to be educated to an internationally competitive level. It is a fallacy to think that new technologies developed elsewhere in the world can be simply imported as needed. Without the scientific infrastructure and supply of research personnel, the needs often go unrecognized until it is too late to establish a competitive edge in the market, and the implementation of new technologies requires people who understand them and can advance the state of the art.

Canada needs atmospheric and space research because of growing concerns about our environment. The main thrust is to understand better the complex dynamics of the atmosphere and its relationship to atmospheric processes such as depletion of the ozone layer and global warming. The interaction of the outer edges of the atmosphere with the near space environment ia a rapidly growing area of study in Canada and elsewhere. It is important for Canada to remain a part of this global effort at all levels. Atmospheric studies and space research rely heavily on both the basic atomic and molecular data and the instrumentation provided by General Physics. For example, laser sounding (lidar) provides an important technique for monitoring pollutants, and a vast wealth of atomic and molecular data is required to understand the results. Plasma physics plays a critical role in the upper atmosphere. There is a very direct connection between the instrumentation required for satellite payloads and Canadian high technology industry through the programs of the Canadian Space Agency. This has resulted directly in the creation of several Canadian companies to manufacture the instrumentation.

Canada needs to support research in general relativity and gravity because this is perhaps the most exciting intellectual venture of our time. It is one of the few areas of physics that can capture the public imagination. The dramatic success of Steven Hawking's book *A Brief History of Time* is clear testimony to this. It is also an area where Canada has established a strong reputation, and can continue to make important contributions for a relatively small expenditure. Moreover, it provides a superb education for students in all areas of theoretical physics. As emphasized throughout this document, there is an essential unity to physics which transcends subdisciplinary boundaries. This is especially true for theoretical and mathematical physics, where techniques developed in one area are readily transferable to other areas. The ultimate goal is to find a relatively small number of underlying principles in terms of which all phenomena, including the origin of the universe and its eventual fate, can be understood.

Recommendations Concerning NSERC Funding Policy

To carry out the Committee's detailed mandate (see Sect. 1.2, p. 4), a questionaire was used to poll the community and the responses were used as a basis for the following recommendations:

Selectivity in Research Funding. (see Sect. 12.1, p. 85) Most respondents who answered are satisfied with the current degree of selectivity exercised by the NSERC Grant Selection Committees in awarding grants. However, a substantial number (22 out of 69) did not answer, or gave a rationale indicating that there is no simple answer. Comments indicated that many people feel frustrated with the current levels of funding, and are torn between the need to support good work at internationally competitive levels through greater selectivity, and the need to maintain a broad research base in all universities with emphasis on the training of students at both the undergraduate and graduate levels. The kind of science supported is supremely well suited to the training of students, but many people feel that funding levels are already at or below the critical level to accomplish both objectives.

> **Recommendation 3.** Given the current tensions due to underfunding in the NSERC granting system, it is important to preserve sufficient selectivity to support research at an internationally competitive level, while still maintaining a broad base of university research.

Regional and Geographical Distribution. (see Sect. 12.2, p. 88) As with the preceding item on selectivity, there is a strong dichotomy in the perceived purpose of NSERC grants between the support of research *per se*, and the role of research in the education of students at both the graduate and undergraduate levels. On balance, the recommendation is:

> **Recommendation 4.** Quality and merit should be the principal criteria. Regional and geographical issues *per se* should not be taken into account.

Support of Researchers in Smaller Universities. (see Sect. 12.3, p. 89) The majority of those who responded (24 out of 46) answered "yes" on the grounds that either (1) good research should be supported wherever it is found, but the needs are greater in smaller universities due to lower levels of infrastructure support, and/or (2) it is necessary to support research in all universities since it is an essential component of good teaching at both the undergraduate and graduate levels. Those who answered "no" (20 out of 46) argued that quality and significance should be the only criteria in times when levels of funding are under severe pressure. We must identify those things that we do best and fund them well. On balance, the recommendation is:

> **Recommendation 5.** Quality and significance should remain the principal criteria. However, a broad base of research diversity and educational quality is best maintained if the special needs for support in smaller universities are also taken into account.

This would help avoid the emergence of a two-tier university system consisting of research "haves" and "have-nots", and their consequent differences in quality.

Support of Risk-taking and Diversity in Research. (see Sect. 12.4, p. 90, and Sect. 15, p. 99) As already discussed, General Physics is by its very nature diverse, yet unified by common elements. Concerning risk-taking, most respondents saw this as an important part of the NSERC granting system, but many questioned its usefulness as a separate criterion in judging proposals. A vigorous research program should contain a balance of short-term projects likely to yield useful results (i.e. low risk), and longer term projects of a more exploratory nature (i.e. high risk). The latter type are more likely to lead to dramatic new advances, but are also more likely to be curtailed in times of reduced funding. Specifically "high-risk" proposals whose aim is to obtain some immediate pay-off should be treated with considerable caution.

> **Recommendation 6.** Risk-taking and diversity are factors that should be taken into account by GSC's, but not necessarily more so than is currently the case. Quality and excellence should be paramount. Perhaps some small fraction of the GSC budget could be set aside for projects specifically identified as potential commercial products, and progress carefully monitored.

Minimum and Maximum Grant sizes (see Sect. 12.5, p. 91, and Sect. 12.6, p. 92)

> **Recommendation 7.** The minimum useful grant for experimentalists is normally around \$20,000. For theorists, the minimum useful amount is probably closer to \$10,000.

Some allowance for grants in the lower range is important for the maintenance of diversity in research, and the preservation of a broad research base for the education of students. It does not follow from the need for selectivity that those at the lower end of grants should be automatically cut off if the work is of high quality, though perhaps low in volume, and the needs of the researcher are being adequately met.

> **Recommendation 8.** There should not be an upper limit on grant sizes. The main criterion should be the ability to make good use of the funding.

Comments on Startup Grants (see Sect. 12.7, p. 92) Given the current tightness of funding, there seems little room for expansion at the expense of established researchers. However, several people suggested that there should be greater encouragement for partnerships between NSERC and the universities to provide appropriate levels of funding for the establishment of new laboratories.

Comments on Equipment Grants (see Sect. 12.8, p. 92) Virtually all experimentalists and many theorists pointed out the urgent need to replace obsolete or worn out equipment, and complained that the success rate for equipment grant applications is too low. There is an overall lack of infrastructure support for equipment, especially now that infrastructure grants have been phased out. In addition, equipment grant applications for computers are putting a further strain on funds available for more traditional types of equipment.

One respondent noted in particular the time delays associated with equipment grant applications, which puts him/her at a competitive disadvantage relative to colleagues elsewhere in the world, and suggested an "open date" policy for equipment grant applications with no submission deadline.

Recommendation 9. Additional funding is urgently needed to maintain the infrastructure of research equipment. NSERC should investigate the possibility of holding more frequent competitions for minor equipment grant applications.

Participation in Collaborative Projects. (see Sect. 13, p. 93) Nearly 60% of respondents reported collaborations with colleagues in other universities, and of the 66 collaborations mentioned, 83% were with universities outside of Canada, primarily in Europe, Japan and the United States. This indicates the high degree of influence that Canadian physics research has on other scientists around the world. Second, nearly 1/3 of the respondents reported collaborations with industry, and also 1/3 with other disciplines. The specific industries and disciplines mentioned are listed in Tables 14 (p. 94) and 15 (p. 94). Both these lists are certainly only a partial representation of the total activities in the community.

In atmospheric physics and space science, collaborative projects with industry and other institutions play a particularly prominent role because projects funded by the CSA require a formal industrial partnership, and the projects are often too large to be handled by a single institution.

Encouragement of Research Partnerships with Industry. (see Sect. 14, p. 97) Although the university research community clearly recognizes the importance of research partnerships with industry, nearly half (12 out of 25) expressed concern that sufficient funds were already being thus directed through existing granting mechanisms, research institutes, and networks of excellence. About 1/3 of the respondents have already established various types of industrial collaborations. They questioned whether it is the proper role for NSERC to provide further support for industrially related research. They argued that existing scientific and economic forces were sufficient to bring about collaborations if they were really justified.

Other comments indicated that additional indirect support is needed for the creation of industrial partnerships, as outlined in the following recommendation.

Recommendation 10. Rather than diverting further research monies to encourage industrial partnerships, better indirect support is needed through the provision of match-making services by NSERC (or NRC), and information on how to go about creating an industrial partnership. Also, a graded level of expected industrial contribution, dependent on the size of the company, might be beneficial.

Role of NSERC in Spin-off Activities and Ventures. (see Sect. 16, p. 100) The questionnaire responses indicated that spin-off activities and ventures leading to the formation of new high-tech companies is a vital contribution of physics research to the Canadian economy. Several "success stories" are cited as examples in Sect. 10.2 (p. 72). However, most respondents felt that the provision of venture capital should not be the role of NSERC, or that it is already sufficiently emphasized by existing programs. The financial incentives of a successful spin-off venture provide sufficient encouragement in the current funding environment. The principal aim of university research should be to train people with the best projects and facilities. Ventures into the business world are secondary to this principal mission. It is often the students who ultimately establish spin-off companies, or transfer technological advances to industry.

Communication with other Disciplines and the Public. (see Sect. 17, p. 101) Many responses centred around the creation of science programs in the media to highlight Canadian success stories. NSERC, NRC and Industry Canada might collaborate with CBC to produce regular TV broadcasts featuring Canadian research and development. Other suggestions included the creation of data bases for journalists, and the support of speakers who can communicate well. A strategy now being adopted in the U.S. is the printing of single-page pamphlets highlighting a recent advance and its importance to the public. It should be suitable for journalists and members of Parliament. Workshops for potential users of research in industry or other disciplines would be beneficial.

Participation in Interdisciplinary Research. (see Sect. 18, p. 102) In an important sense, physics is the original interdisciplinary science in that the aim is to bring an ever-expanding range of phenomena from various disciplines under a common umbrella of understanding. Physics is the *enabling* discipline in that it provides the fundamental principles, data, instrumentation and technology that find wide application in other disciplines. These applications often provide the motivation for research proposals in physics. Some subareas such as plasma physics and atmospheric physics/space science are by their very nature interdisciplinary. In this sense, interdisciplinary research is a natural part of the progress of physics, and it is one of its strongest features. About 1/3 of the respondents are already participating in research projects directly involving other disciplines. Most felt that such interactions should be allowed to evolve naturally, and new NSERC initiatives would only encourage exercises in grantsmanship.

> **Recommendation 11.** Since physics is by nature interdisciplinary, new NSERC initiatives to encourage interdisciplinary research *per se* are not needed. Interdisciplinary collaboration should not be regarded as an end in its own right.

However, our proposal for a new initiative in laser science and spectroscopy is strongly interdisciplinary in its potential applications, and additional funding would provide direct support for these applications. The introduction of a laser science panel of experts would be useful in the adjudication of interdisciplinary applications in this area.

Enhancement of the Impact of Physics Research on other Disciplines. (see Sect. 19, p. 103) The impact of physics research is already very profound and far reaching. Much of engineering is largely "applied physics", including the most recent research findings involving lasers, photonics, nonlinear optics, plasma processing, detection devices, and computer modelling techniques. Despite this, more should be done to advertise the generally applicable skills of physicists in computing and the mathematical modelling of physical systems, as well as specific experimental techniques. Existing interdisciplinary conferences such as the Interdisciplinary Laser Science Conference, or the annual Waterloo Chemical Physics Symposium are very useful. More interdisciplinary talks could be included in the annual CAP Congress, and the CAP executive could similarly take the initiative in suggesting appropriate physicists to speak at the annual meetings of other disciplines. Other means of communicating research results to other disciplines have already been mentioned.

In general, physicists should get more directly involved with other branches of science and engineering, and demonstrate their capabilities to industry. However, most respondents viewed specific new programs by NSERC to encourage this as likely to be ineffective and overly costly relative to their benefits. What is needed is better funding for the basic NSERC programs of operating grants and equipment.

Effect of a 15% Increase or Decrease in Funding. (see Sect. 21, p. 109) Since changes in funding levels would not be spread uniformly across the discipline, respondents were asked to consider the effect of a doubling or halving of their research grants. Many respondents indicated that their research grants were now at or below the critical level to maintain a viable and internationally competitive research group. The impact of a change in funding would therefore be particularly great. At present levels of under-funding, it is the longer term higher-risk research of a more exploratory nature that particularly suffers in favour of short term projects likely to yield quick results. With an increase in funding, most indicated that they could take on additional graduate students or postdoctoral fellows, and undertake a broad range of new initiatives on the exciting themes identified in Table 21 (p. 105). With a decrease in funding, research would become so marginalized that many researchers would shut down their programs altogether.

The problems are compounded by progressive cut-backs in the levels of infrastructure support (such as machine and electronics shops) provided by universities, resulting in further drains on research grants and demands on the researcher's time.

> **Recommendation 12.** Since research grants in physics are at or below the critical level for viability, an increase is urgently needed, especially for the support of newly emerging areas involving laser development, the cooling and trapping of atoms, and the applications of photonics to telecommunications. A further cut would seriously cripple the research capability and production of highly qualified personnel in all areas.

Role of Research in the Education of Students (see Sect. 22, p. 113) Nearly all respondents reported that their involvement in research improves their teaching, and research clearly plays a central role in the education of graduate students. The kind of "small physics" research projects typically supported by GSC-29 is ideally suited to this purpose because students become involved in all aspects of an experiment from the initial design and construction to the taking of data and subsequent analysis. In the process, they learn a broad range of skills that can be directly transferred to high technology industry, as discussed in Sect. 10.2 (p. 72). The same is true for students involved in theoretical projects, which typically involve a blend of mathematical analysis and computer programming.

In addition, nearly all respondents reported that they involve undergraduate students in research projects, and that this forms an important part of their education.

> **Recommendation 13.** The important role of research in the education of students should be clearly recognized, for example through programs similar to those supported in the U.S. by the NSF, NASA, and DOE.

The Status and Future of General/Space/Atmospheric Physics and General Relativity in Canada

NSERC/CAP Review of Physics
General/Space/Atmospheric Physics and General Relativity Subcommittee [1]

May 26, 1997.

1 Introduction

The Canadian Association of Physicists (CAP) and the Natural Sciences and Engineering Research Council (NSERC) Physics Liaison Committee proposed in February 1996 a wide-ranging review of Canadian academic physics to identify both its strengths and weaknesses, and to provide NSERC and the physics research community with the information to make recommendations to build on these strengths and to address the weaknesses. Following the award of funding by NSERC in the spring of 1996, CAP established an independent Review Committee consisting of four subcommittees to deal with the various subareas of physics in parallel with the structure of the NSERC Grant Selection Committees (GSCs). The Main Committee is chaired by Dr. W. P. Halperin (Northwestern University), and the subcommittees are:

- Condensed Matter, GSC-28 (Michael Thewalt, chair)
- General/Space/Atmospheric Physics and General Relativity, GSC-29 and GSC-17 (Gordon Drake, chair)
- Subatomic Physics, GSC-19 (Faqir Khanna and Pekka Sinervo, co-chairs)
- Highly Qualified Personnel and Economic Aspects (Bev Robertson, chair).

The purpose of this report is to review the parts of physics supported by GSC-29 and GSC-17. With the approval of the Canadian Astronomical Society (CASCA), the Atmospheric Physics and Space Science communities (GSC-17) agreed to combine forces with General Physics (GSC-29) for purposes of conducting a survey and preparing this report. However, for reasons discussed in Appendix A.2 (p. 123), the large astrophysics and astronomy component of GSC-17 is not included in the survey.

General Physics includes a wide diversity of topics which by definition do not fall under either of the headings *Condensed Matter Physics*, or *Subatomic Physics*. At first sight, one might think that this would lead to a random assortment of loosely connected topics. A primary objective of this report is to show that, despite the diversity, the field as it exists in Canada is strongly linked together by common themes of current interest. As shown in Fig. 1, the main topics of atomic and

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molecular properties, laser developments, plasma physics, atmospheric/space science, and various applications all flow from the two main headings of

1. Lasers and their many varied applications, and
2. Interactions between atomic and molecular species.

These two topics are themselves closely linked together because the properties of lasers are strongly influenced by atomic and molecular interactions, and the steady advances in the capabilities of lasers provide ever more powerful methods for determining the properties of atoms and molecules and their interactions.

The various topics are also strongly linked together by common bonds of theoretical understanding and computational technique. This is illustrated by the bottom portion of Fig. 1 and the lines connecting it with the top part. Not shown are further linkages of common experimental and/or theoretical technique connecting the upper and lower portions separately amongst themselves.

A second objective of this report is to bring out the importance of the topics covered by General Physics to the overall advancement of science and its technological applications. As the most basic of the sciences, General Physics describes phenomena on an energy scale ranging from the everyday world around us to that of nuclear physics. It provides the information base and technologies on which all other applications rest. Since the time of Newton and Maxwell, the aim of physics has been to bring an ever widening range of phenomena under a common umbrella of understanding. In this sense, General Physics has grown from interdisciplinary roots, and it remains strongly so today. It is therefore not surprising to find a wide range of topics covered in Fig. 1. This should be regarded as a strength, rather than a weakness. It indicates that General Physics is a flexible and dynamic discipline able to respond quickly to new initiatives, and to bring diverse methodologies to bear on a new problem.

In summary, General Physics is both a *basic* and an *enabling* science. It is basic in that it seeks to identify the principles underlying natural phenomena and to unify understanding. It is enabling in that it provides the techniques and methodologies for a wide diversity of interdisciplinary applications. It covers a continuous spectrum of activities ranging from the most fundamental to practical engineering applications. The most outstanding recent example is the laser with its many applications ranging from eye surgery to fibre optics and communications. By its very nature and tradition, General Physics is interdisciplinary.

1.1 Relationship to Condensed Matter Physics (GSC-28)

The growth of different research communities within physics has led to separate NSERC Grant Selection Committees (GSCs) to award research grants in the different areas (see Sect. A.1, p. 121). However, as will be emphasized in this document, physics as a whole is a discipline that is strongly unified by underlying themes of theory, experimental technique and applications to other areas. The division along GSC lines into "General Physics" and "Condensed Matter Physics" is therefore somewhat arbitrary and by no means clear cut. There are very strong areas of overlap, especially in the areas of surface physics, materials science, photonics, and laser science, as well as theoretical techniques that cut across all the subdiscipline boundaries. Although separate reports are being prepared for General Physics (GSC-29) and Condensed Matter Physics (GSC-28), this should not be taken as a signal that the two branches of physics can be considered as disjoint blocks. In fact, one of the major recommendations will be for a new initiative in laser science and its many applications. As will become evident from the material to follow, the successful implementation of this initiative will require a close collaboration between researchers supported by GSC's 28 and 29,

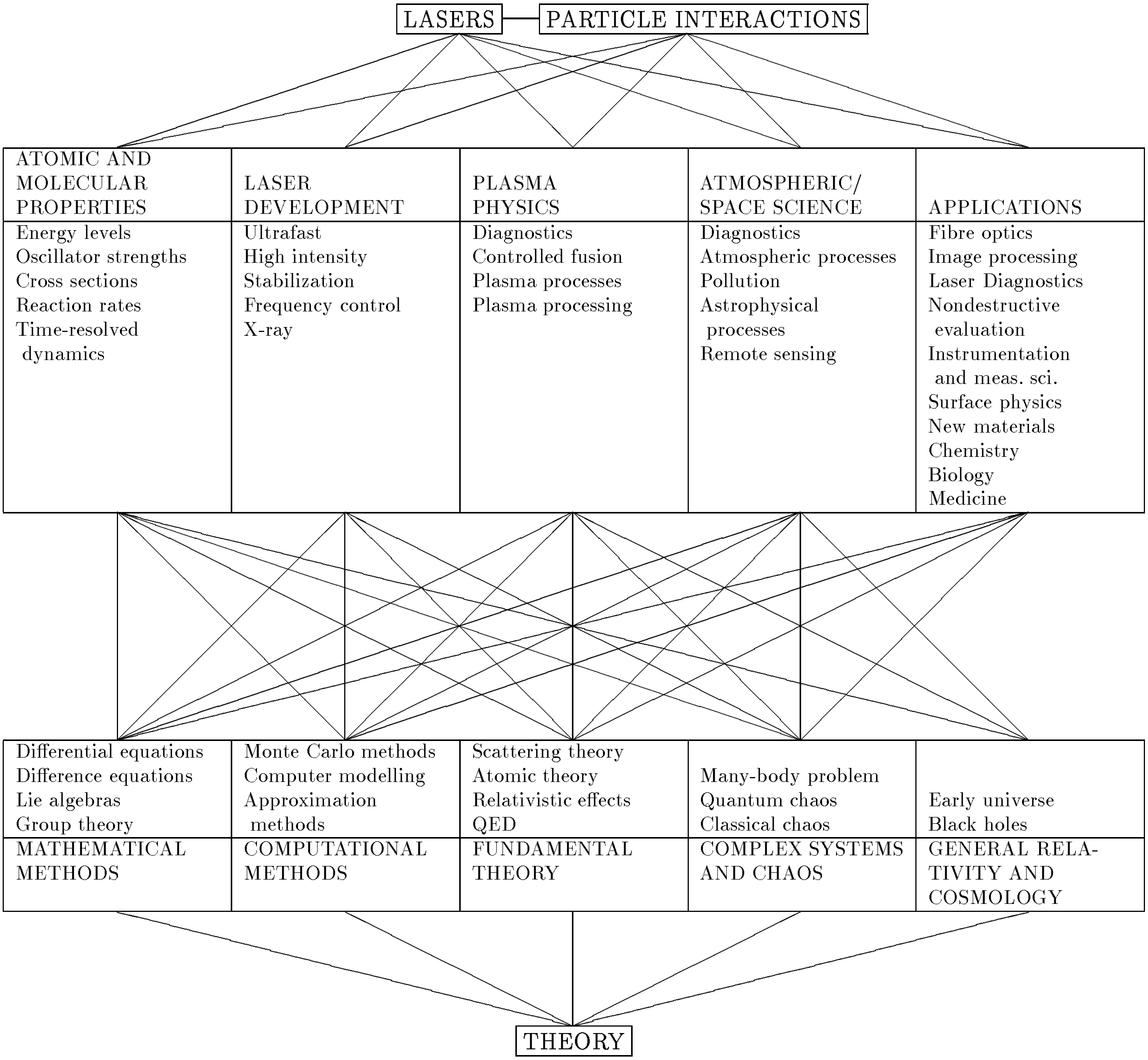

Figure 1: Fields covered by General Physics and their interconnections.

especially in the areas of laser physics, laser-surface interactions, photonics, nonlinear interactions and materials science. This report is written in a spirit of subdisciplinary cooperation between GSC's 28 and 29.

1.2 Terms of Reference

The General/Space/Atmospheric Physics and General Relativity Subcommittee was given a ten point charge, which we have paraphrased as follows:

1. To survey current and planned academic research in general physics, atmospheric physics and space science, and general relativity (Sects. 2 to 8).
2. To identify strengths and weaknesses in the Canadian physics research program (Sect. 9, p. 59).
3. To identify particular areas of focus for future research, maintaining both diversity and risk-taking to ensure a successful research enterprise (Sect. 11, p. 77).
4. To determine how funding should be distributed to attain the appropriate level of research diversity, focus and risk-taking for the future program (Sect. 12, p. 85).
5. To evaluate how NSERC can encourage risk-taking, spin-off activities, communication with the public and other scientific disciplines, and interdisciplinary research (Sects. 13 to 18).
6. To assess interactions and impact with other disciplines (Sect. 19, p. 103).
7. To consider the potential benefits of encouraging major collaborative efforts across subdiscipline boundaries (Sect. 20, p. 105).
8. To consider the impact of a 15% increase or decrease in funding (Sect. 21, p. 109).
9. To synthesize a "Vision Statement" for general physics, atmospheric physics and space science, and general relativity in Canada (Sect. 23, p. 115).
10. To prepare a preliminary report of the subcommittee's findings, after consultation with the physics community, and to submit the final report to international reviewers.

The terms of reference specifically do not refer to a study of economic impact or the training of highly qualified personnel (HQP) because these questions will be addressed by a separate Subcommittee on Economic Aspects, chaired by Bev Robertson. However, many anecdotal examples of economic impact are contained in this report (see especially Sect. 10.2, p. 72). In addition, Sects. 14.1 (p. 97) and 22 (p. 113) discuss the role of students in technological transfer to industry, and the role of research in the education of students.

A primary motivation for this report is the NSERC Grant Reallocation Exercise discussed in Sect. A.2 (p. 123), and the background work required to prepare for the next redistribution of NSERC funds among disciplines. An underlying theme of the terms of reference is therefore the need to show why the programs supported by NSERC are of "benefit to Canada." The various threads relating to this question are drawn together in the Executive Summary (p. ix).

The subcommittee's report will be provided to a set of external reviewers, who will be asked to give written assessments of the scientific quality of the program. These assessments, together with the reports from all the subcommittees, will provide the basis for further discussion and planning within the Canadian physics community.

This report is intended to be read by several different audiences. First and foremost, it provides the external reviewers with a coherent description of General Physics research in Canada, an evaluation of the strengths and weaknesses of the research program, and it addresses the other points in our charge. Second, it will be used by the Main Committee to prepare an Executive

Summary that will integrate the conclusions of all four subcommittees. Third, it forms the basis for future consultation between the physics research community and the NSERC GSCs responsible for reviewing and recommending funding for specific research projects. Finally, this report provides some of the data that will be used in the next NSERC Reallocation to determine future NSERC funding levels for the discipline.

1.3 Methodology

A proposal for this review was presented to NSERC by the CAP Physics Liaison Committee in October, 1995, and funding approved for it in March 1996. Work then began immediately on setting up the various subcommittees and appointing their chairs in consultation with CAP, including the present one to evaluate the research programs defined by GSCs 17 and 29. The subcommittee held a town hall meeting at the June, 1996 CAP Congress to solicit input from the community. At that time, the subcommittee defined in broad terms the manner in which it would achieve its goals.

In August, 1996, the subcommittee sent an in-depth survey by mail to all NSERC grant-eligible applicants, and by electronic mail to all members of CAP. A copy of the questionnaire used is reproduced in Appendix E (p. 155). During the months of September and October, members of the subcommittee contacted all those who had not responded to the survey in order to encourage a response. Eventually, 69 responses were received. Of these, 52 were from researchers supported by GSC-29 (out of a total population of 141, or 37%), 15 were from researchers supported by GSC-17 (out of a total population of 152, or 10%), and the remaining two were from individuals not supported by NSERC. The low response rate from members of GSC-17 reflects their closer affiliation with CASCA (Canadian Astronomical Society) than with CAP (see Appendix A.2, p. 123 for further discussion of participation by the astronomy and astrophysics communities).

During November 1996, the responses were distributed to the appropriate member of the subcommittee who analysed the results and prepared summary statements. Our analysis of the survey forms the basis for many of our recommendations. The summary statements were then combined with additional material to produce a preliminary *Draft for Discussion*, which was distributed as a hard copy to the members of the subcommittee on February 22, 1997, and to an extensive list of other members of the community. It was also made available through the University of Toronto web site on February 28, 1997, and all members of CAP notified that they could see it there, or request a hard copy.

A large number of responses to the *Draft for Discussion* was received pointing out errors and omissions (in many cases substantial), and making suggestions for improvement. This additional material has helped tremendously in producing what we believe is a much improved document. However, the time available was barely sufficient to assemble the material into a coherent form, and much more could be said in many of the areas covered. A *Semifinal* revised version of the report was distributed to the International Assessors on April 16, 1997, and an updated version was distributed at a meeting with the International Assessors on May 6, 1997 in Cambridge. The present May 26, 1967 version contains further additions and changes agreed upon there.

1.4 General Approach and Organization

A survey of this scope and magnitude has not been carried out in Canada since 1981 when reports were written for the various subfields under the CAP/NSERC *Future Research Opportunities in Canada* initiative. At that time, separate committees were formed and reports written for each of the areas covered by the present report; i.e., Atomic and Molecular Physics [1], Optics [2], Plasma Physics [3], and Space Physics [4]. Since much has happened in the intervening years, these reports are now of little value, except that they still contain useful background material. The task of integrating all of these areas into a single document is much greater, but it provides an opportunity to draw out their close interrelationships and the underlying unity of physics. It is also instructive to place each of the areas discussed into their proper historical context since there was little high-calibre physics being done in Canada before the 1950's, and excellence does not just appear out of nowhere. The historical sketches also provide interesting profiles of institutional development. The complexity of the present report is further increased by the need to address the other items in our charge, as outlined in Sect. 1.2.

The rest of this document is organized in parallel with the ten items in our charge, according to the section numbering shown in Sect. 1.2. Section 2 provides a general discussion of the historical development of general physics research in Canada, followed by overviews of the current research programs (Sects. 3 to 8), discussions of strengths and weaknesses (Sect. 9, p. 59), anecdotal examples of scientific and applied "success stories" (Sect. 10.1, p. 67), and future areas of focus (Sect. 11, p. 77). The subsequent Sections 12 to 22 deal with the specific items in our charge relating to NSERC funding policies. The document concludes with "vision statements" for each of the areas (Sect. 23, p. 115). A statement of why the support of these areas is of benefit to Canada is given in the Executive Summary (p. ix). Appendix A (p. 119) provides background material on the funding of academic research in Canada. This should be read by those who are not familiar with the NSERC granting system. Appendices C and D provide detailed listings of the grantees supported by GSCs 29 and 17 respectively. The questionnaire is reproduced in Appendix E. Appendix F provides a glossary of technical terms, and Appendix G lists definitions for the various acronyms and abbreviations used in the text.

2 The Development of General Physics in Canada

The current high level of Canadian research in lasers, plasma physics, optical physics, and particle interactions has grown from a long tradition of Canadian excellence in the area of atomic, molecular and optical physics, and its applications. This section begins with a brief review of the historical development of atomic and molecular physics in order to provide an appropriate background, followed by a survey by university and region of current activities.

2.1 General Background

Atomic and molecular physics has played a central role in the overall development of modern physics. Although its roots date back to the early 1800's, the field is currently being revitalized by the relentless advance in the power and capabilities of lasers, and by parallel advances in computers.

Laboratory spectroscopy became possible with the development of electrical discharges, and by 1900 this had evolved into the physicist's most precise tool for identifying substances and investigating the structure of matter. Regularities discovered by spectroscopists in the spectra of simple atoms led directly to the early quantum theory of Bohr in 1915, and its modern counterpart introduced by Schrödinger in 1925. This was followed by an intense period of activity in university laboratories around the world to test the predictions of quantum mechanics in a variety of atomic and molecular systems. Quantum mechanics was also rapidly applied to explain the foundations of chemistry, both from the point of view of molecular structure and the theory of reaction rates. This has now reached a high degree of sophistication.

By 1935, the basic ground work had been established and, especially during the war years, many physicists turned their attention to the more immediately pressing problems of nuclear physics and electronics.

The rebirth of atomic and molecular physics as an academic discipline began slowly in the 1950's for a combination of academic and nonacademic reasons. First, urgent new needs for basic atomic and molecular data came on the horizon from industry, the atomic energy program, the space program and government. Secondly, a number of new experimental techniques were developed, especially in the areas of electron-atom, atom-atom and ion-atom collisions. Advanced electronic techniques for the acquisition of data and control of experiments played an important role. Thirdly, the development of computers in the 1950's and 1960's made possible a whole host of theoretical calculations for the analysis and interpretation of experimental results. Thus, both the practical needs and the means were present for a fresh flowering of the subject as an academic discipline in many universities around the world. The timing of these developments coincided with a massive expansion of the Canadian university system during the 1960's.

Since then, the field has constantly been revitalized by the discovery of new phenomena and applications, and the development of new experimental techniques. Especially important is the invention of the laser. The development of new laser systems flows directly from basic atomic and molecular physics. The laser in turn opens up the possibility of a wide diversity of new experiments and applications which were previously impractical. For example, ultrashort laser pulses now make it possible to follow the detailed course of chemical reactions. Also, various "exotic" atoms containing nonstandard particles such as positrons and muons are now available for study. Finally, new applications and demands for basic atomic and molecular data constantly present themselves in other fields such as astrophysics, atmospheric physics, plasma physics, biology, medicine, and the controlled fusion program. For these reasons, atomic and molecular physics remains a vital and growing field of study.

2.2 Survey of Programs

The history of atomic and molecular physics in Canada has followed a similar course. Prior to World War II there were no large physics research centers in Canada. However, atomic and molecular physics played a prominent role in the work of well-known scientists from that era. An outstanding example is the precise spectroscopic measurement of term values and investigations of the aurora by J. C. McLennan at the University of Toronto in the early 1900's. In the 1920's, J. S. Foster at McGill University did very significant work on the Stark effect in helium and other atoms. Further important spectroscopic work on hyperfine structure was done by Lang at the University of Alberta. G. Herzberg, the best known of Canadian scientists and one of our Nobel Prize winners, did much of his early work on the spectra of molecules at the University of Saskatchewan.

As a guide to the material to follow, the current NSERC research programs supported by GSC-29 (General Physics) and GSC-17 (Atmospheric Physics and Space Science) are summarized in Appendices C and D respectively, classified both by university and by subarea of study.

2.2.1 Ontario Universities

In parallel with the gradual rebirth of atomic and molecular physics elsewhere in the world following the Second World War, larger centres of activity began to develop in Canada. At the University of Toronto, M. F. Crawford and his students began applying newly developed atomic beam techniques to the investigation of atomic properties. At about the same time, H. L. Welsh initiated his research program on high-resolution Raman spectroscopy, and discovered the phenomenon of pressure-induced infrared absorption in gases. For the next two decades, these two research programs became the mainstays of molecular physics research at Toronto, producing a large number of Ph.D. graduates and providing training to many postdoctoral fellows from all parts of the world. B. Stoicheff has become particularly well known for his work on laser spectroscopy, a technique which he has applied with great success to the study of the Raman effect, Brillouin scattering, and the pressure broadening of atomic Rydberg states. He was the first Canadian to construct a laser shortly after the development of the ruby laser in 1960. During the 1970s he and his group were instrumental in producing a numbre of breakthroughs in excimer laser technology that were subsequently commercialized by Lumonics in Ottawa.

An important development at the University of Toronto was the establishment of the Ontario Laser and Lightwave Research Centre (OLLRC) in 1988, with funding from the Ontario Centres of Excellence program and an annual budget of about \$4.5 million shared among groups from Chemistry, Engineering, Medicine and Physics. The mission of the OLLRC is

> to support outstanding laser and lightwave research that enchances the knowledge base in Ontario and provides the foundation for technology-based innovation; to support industrial growth and wealth generation through partnerships with industries in Ontario and through technology transfer and diffusion; and to train and develop highly skilled personnel to meed the needs of Ontario industry.

This mission statement, appropriately generalized, also summarizes the mission of much of the other work classified as "General Physics" in the rest of Canada. Most of the atomic, molecular and optical work at the University of Toronto (May, Stoicheff), as well as laser-surface interactions and laser development (Herman, Marjoribanks, Smith, Steinberg, van Driel), now centres around the OLLRC. The development of novel laser systems and their applications is an important part of their program. A notable example is the success of R. M. Measures in the use of embedded optical fibres to monitor structural strains in bridges etc. This has now been successfully commercialized through his company Electrophonics (see Sect. 10.2, p. 72). The connections of this work with plasma physics and with atmospheric physics (UTIAS) are discussed in Sects. 5 (p. 29) and 6.1 (p. 34) respectively. The OLLRC is an excellent example of interdisciplinary work brought about by the laser.

A similar pattern of growth from the 1950's onward occurred at the University of Western Ontario. There, the primary motivation was provided by a long-standing program of ground-based and rocket-borne studies of the upper atmosphere and aurora. In response to the emerging need for basic spectroscopic data, and for other projects related to the space program, R. W. Nicholls initiated a comprehensive program for the combined experimental and theoretical study of the spectra of diatomic molecules. Subsequent work by the Western group included studies of excitations in ion-molecule collisions (Mitchell), spectral line shape and differential cross section measurements, and high precision work of fundamental importance using ion beam spectroscopy (Holt, Rosner). Much theoretical work was done on electron and positron scattering, photoionization, scattering resonances, and atomic and molecular structure theory (Goldman, Luke, Talman). In 1973, researchers from several departments formed the Centre for Interdisciplinary Studies in Chemical Physics (CCP). Some of the interdisciplinary studies include the use of lasers to study biological systems, and the use of x-rays and ion beams in the fabrication of VLSI microcircuitry. In recent years, the program has evolved progressively toward surface physics and related applications.

At York University, the Centre for Experimental Space Science (CRESS) was founded by R. W. Nicholls in 1965. Since then, their atomic and molecular physics work has focused on problems relating to atmospheric studies, space and astrophysics. Many important studies have been made of the chemical kinetics of atomic, molecular and ionic species found in the earth's atmosphere, planetary atmospheres, comets, etc., in addition to spectroscopic studies of similar species for diagnostic applications. The laboratory work has been well supported by several theorists in the group working on calculations of collisional cross sections (Horbatsch, McEachran, Stauffer), radiative transition rates and other atomic properties (Darewych, Freedhoff), synthetic spectra, and models of atmospheric phenomena. These data on the basic properties of atoms and molecules play an essential role in the interpretation of atmospheric and astrophysical observations. More recent work includes the innovative use of lasers to make high precision measurements of atomic properties, and to obtain data of fundamental importance in comparison with theory (van Wijngaarden, Hessels).

An important feature of CRESS is they way in which it has encouraged multidisciplinary research programs in chemical physics, atmospheric science, astronomy and astrophysics. The Centre has evolved to include also earth science and computer science researchers. In 1973, A. I. Carswell initiated the highly successful Optech Company to exploit the uses of laser radar (lidar) for the remote sensing of atmospheric phenomena (see Sect. 10.2, p. 72).

At the University of Windsor, research in atomic and molecular physics began in 1958 when Lucjan Krause initiated a program to investigate a broad range of gas phase collision phenomena involving a variety of optical excitation and energy transfer processes. The motivation is to study the various ways in which energy is transmitted via collisions and electromagnetic radiation, with applications to atmospheric processes, the lighting industry etc. Since 1960, the basic thrust of the Department has been to develop atomic, molecular and optical physics as its major area of research activity. This initiative was greatly aided by the award of an NRC Negotiated Development Grant in 1970. As a result, the scope of activities was extended to include a highly productive experimental program to measure cross sections for a variety of electron-atom and electron molecule scattering processes, angular correlations and polarization phenomena (McConkey). Also, laser development, and the application of lasers as an excitation source for molecular spectroscopy and the study of gas phase excitation transfer and related collision phenomena were added (Atkinson, Czajkowski, Krause). The theoretical part of the program (Baylis, Drake) has been notably successful in the high precision calculation of atomic properties, line shapes, exotic radiative transitions of astrophysical importance, and the development of new theory to properly describe relativistic and quantum electrodynamic effects in helium and other multi-electron atoms (see Sect. 3.5, p. 24). A joint theoretical-experimental collaboration (Drake, van Wijngaarden) has been in progress since 1974 to develop an alternative high-precision method for measuring the Lamb shift in hydrogenic systems. Since 1989, the use of atomic and molecular techniques in the study of clusters and surfaces (McConkey, Schlesinger) has been increasingly emphasized as part of an interdisciplinary program involving also chemistry, mechanical engineering and computer science. As an indication of the international stature of the program, Windsor will be hosting the International Conference on Atomic Physics in 1998.

At the Universities of Guelph and Waterloo, atomic and molecular physics has grown since the 1950's along with the overall development of these two institutions, with close collaboration because of their geographical proximity. In addition to the work supported directly by GSC-29, there is broad collaboration with other researchers in the Departments of Chemistry and Mathematics, resulting in the formation of the Joint Institute for Molecular Sciences (JIMS). A large part of the research is related in one way or another to the study of low-energy long-range interactions between atoms and molecules, with applications to the bulk transport and relaxation properties of gases and liquids. The experimental techniques include extensive atomic and molecular beam spectroscopy and scattering work, neutron scattering from dense gases and liquids as a probe of three-body and higher order interactions, and atom-surface scattering. At Guelph, these techniques are particularly being applied to the study of C_{60} complexes (Gray), and to the spectroscopy of solid hydrogen and liquid helium excited by proton beams (Hunt, Brooks). They were among the first to observe the HeH molecule. This latter work takes advantage of the unique opportunities provided by combining cryogenics with a particle accelerator. At Waterloo, the work supported by GSC-29 is primarily theoretical, with broad programs for the systematic calculation of cross sections for the excitation and ionization of positive ions by electron and proton impact (Chidichimo), and for the theoretical modelling of molecular dissociation induced by high-intensity laser pulses (Liu).

At Wilfrid Laurier University, active research on thin-film optical devices began with the arrival of J. Lit in 1977. His extensive studies of propagation and coupling phenomena in multilayer thin-film waveguides have led to the development of integrated devices for optical communications. Recent work also includes the rapidly developing field of erbium-doped fibre lasers (Lit) and quantum well lasers (Wartak).

Although much of the work at McMaster University is in the area of condensed matter and subatomic physics, there is a very active program in optics and the development of optical devices that straddles General Physics, Condensed Matter Physics, and Engineering Physics. The topics covered in optoelectronics and photonics parallel many of those at Toronto (OLLRC) and Laval (COPL) (see Sects. 4.1 and 4.2, p. 26), but in the case of McMaster they are supported primarily by GSC-28 or the Engineering GSC's. Of the research supported by GSC-29, D. Cassidy works on the development of semiconductor diode lasers such as InGaAsP devices, and their applications to many different areas such as trace gas detection and telecommunications. Haugen exploits nonlinear optical conversion to reach the wavelength ranges needed for the multiphoton excitation of negative ions to autodetaching states. This process provides a key destruction mechanism for negative ions in the upper atmosphere and low density plasmas. The work involves a close collaboration with the storage ring facility in Aarhus, Denmark, and has important applications to accelerator-based mass spectrometry.

At the University of Ottawa, the laboratory of P. Marmet has made many seminal contributions to studies of electron impact excitation and ionization processes in atoms, ions and molecules, and high resolution electron spectrometry. Particularly important are high resolution studies of electron scattering resonances and their comparison with scattering theory. Also at Ottawa are the widely cited theoretical programs of Varshni, Hodgson and L'Heureux. These are further discussed in Sect. 8 (p. 53).

At Carleton University, Johns and McKee are conducting a research program to improve the technology for x-ray imaging and single-photon emission tomography. The primary motivation is the medical applications of these techniques.

2.2.2 Québec Universities

At Laval, the early atomic and molecular research in the 1950's centred around the activities of Larkin Kerwin, especially in the area of mass spectrometry and its development as a powerful technique for the detection and measurement of ionized atomic species. This, together with a broad range of electron impact ionization studies, formed the basis for much of the early work. The group has produced a large number of excellent students, many of whom have established their own research programs either at Laval or at other universities across Canada. As a consequence, a strong tradition of mass spectrometry now exists at several universities, including Laval, McMaster, Manitoba, U.B.C. and Toronto (UTIAS). The subsequent growth at Laval was greatly enhanced by the award of an NRC Negotiated Development Grant in 1969, which led to the formation of the Centre de Recherche Atomique et Moleculaire (CRAM, 1969-89).

In 1990, the CRAM was reorganized into two groups of researchers. In the Physics Department, the Laboratoire de Physique Atomique et Moléculaire (LPAM), founded in the fifties by L. Kerwin, is presently composed of Dubé, Larzillière, Knystautas and D. Roy, with activities complementing themselves around atomic and molecular collisions with gas and solid phases. On a larger scale at the Faculté des Sciences et de Génie, the Centre de Recherche sur les Propriétés des Interfaces et la Catalyse (CERPIC) comprises 12 professors from five departments. CERPIC is truly an interdisciplinary center whose research activities include the study of the properties of surfaces and interfaces of materials, and the development and applications of advanced industrial materials (e.g. heterogeneous catalysors, coatings, metal and organic membranes, materials used in the optical treatment of information). Knystautas and D. Roy (director) are members of the center.

There is also a separate program to study the properties of lasers and the interaction of intense laser radiation with atoms and molecules. For example, up to six electrons can be ejected at once from a molecule. Since the remaining electrons are no longer sufficient to hold the molecule together, the atomic nuclei fly apart in a kind of "Coulomb explosion" whose well-defined patterns can be used to deduce the original molecular structure (Chin). Other recent work includes the application of ultrafast intense laser methods to environmental detection, medicine, electronics and optics. In addition, there is a broad program of beam-foil spectroscopy and atomic lifetime measurements (Knystautas) in conjunction with the van de Graaff accelerator at Laval. This work also includes the use of ion bombardment to produce surface hardening and induce novel changes in the optical and electromechanical properties of materials.

A large and active part of the program at Laval (Arsenault, Bélanger,Denariez-Roberge, Galstain, Lessard, McCarthy, Piché, Sheng, Tremblay, Vall'ee, Villeneuve) is concerned with fibre optics, optical waveguides, image processing, and the nonlinear interactions of intense laser light with materials (photonics). All of this has important applications to the communications industry, as further discussed in Sect. 4 (p. 25).

Elsewhere in Québec, the work of Fontaine at Hull on the numerical simulation of optical birefringence effects in nonlinear media provides theoretical support for the optical physics program at Laval. Similarly, the theoretical work of Grundland on the methods of symmetry reduction and Riemann invariants at Trois-Riviéres contributes to the theoretical understanding of nonlinear phenomena in optics. At Sherbrooke, D. Houde is applying femtosecond time-resolved four-wave mixing as a probe to study phase transitions and charge transfer processes in solids.

General theoretical and mathematical work supported by GSC-29 is largely centred at the Centre de Recherche Mathématique (CRM) at the Université de Montréal (Saint-Aubin, Hussin, Patera, Vinet, Winternitz). This group is very well known for its work on symmetries in physics and the application of group theoretical methods and group representations to the solution of differential and difference equations. Closely associated with CRM are J. Harnad, S. T. Ali and R. L. Hall at Concordia on signal processing and spectral analysis, and R. T. Sharp at McGill. Taken together, this group represents an important resource for the application of the methods of mathematical physics to the solution of physical problems (see also Sect. 8.3, p. 55).

Also at the Université de Montréal, M. Moisan and J. Margot contribute to the fundamental understanding of plasmas through their experimental studies of high frequency discharges. This is further discussed in Sect. 2.3 (p. 19).

2.2.3 Role of the Centre de Recherches Mathématiques

The Centre de Recherches Mathématiques (CRM) is a national resource that is playing a key role in the development of theoretical and mathematical physics in Canada. It receives (like CITA) sizeable funding from NSERC and is also supported by FCAR, the Quebec funding agency, the Université de Montréal and other sources. The CRM is currently directed by Luc Vinet. The mission of the CRM is to promote and carry out research in all the mathematical sciences. This is accomplished in various ways: (i) on-going research projects are carried out by the CRM members, (ii) a large number of scientific activities are organized by the CRM in Montréal and at various sites across the country; in particular the CRM holds every year an important theme program involving distinguished lecture series, workshops, conferences, summer schools and concentration periods of visitors, (iii) the CRM has an active outreach program with business and industry which has recently been boosted with NSERC awarding a research network grant to a consortium of which the CRM is part, (iv) the CRM acts as a publishing house producing at least 150 technical reports per year, and between six and eight books in collections distributed by international companies.

Since its creation in 1968, theoretical and mathematical physics has always been a trademark of the CRM, with many of its star researchers funded by GSC-29. It is determined to keep this profile and it in fact aims to broaden its base in the physics community and to enlarge the spectrum of its research activities in theoretical physics. The CRM has already organized various events in theoretical physics, many of which were in collaboration with CAP. To give a few examples: it sponsored the 1994 CRM-CAP summer school on "Particles and Fields", it organized a workshop on "Theoretical and Mathematical Physics" in the framework of the 1995 CAP Congress, it just held an international workshop on the Calogero-Moser-Sutherland model, and it is supporting the organization of the CRM-Fields-CAP summer institute on solitons to take place next July at Queen's University. In 1995, on the occasion of CAP's 50th anniversary, the CRM proposed the creation of the CAP-CRM prize in theoretical and mathematical physics. This prize, now awarded yearly, has been given to Werner Israel (1995) and Bill Unruh (1996).

The CRM is organizing for 1999-2000 a theme year in Mathematical Physics. This major program will involve activities in areas that include: duality and string theories, integrable systems and statistical models, quasicrystals, turbulence, nonequilibrium statistical mechanics, quantum computers and information theory, general relativity, superconductivity, mesoscopic systems, etc. One aim of the program is to foster interdisciplinary exchange between various subcommunities. A Banff summer school in theoretical physics is also planned in this connection for 1999.

Recently, the CRM reached an agreement with Springer-Verlag to publish a new collection of books entitled the CRM series in Mathematical Physics. The need for this collection illustrates the broad international impact of the mathematical physics being done at the CRM, and its stature in the field.

This brief summary of the CRM's involvement in theoretical and mathematical physics shows the great impact that it has on this most active research area both in Canada and internationally.

2.2.4 Maritime Universities

In the Maritimes, small but significant centres of atomic and molecular physics have developed at Memorial University (Newfoundland), St. Francis Xavier University (Antigonish), and the University of New Brunswick (Fredericton), all beginning in the 1960's. The strong tradition of spectroscopy in Canada is clearly reflected in the activities of all of these centres. The current research activities in atomic and molecular physics of each are outlined below.

At Memorial (Gien, Reddy), the classical spectroscopy of atoms and molecules is supplemented by collision induced absorption measurements, Brillouin scattering and Raman spectroscopy (Reddy). These techniques are being used to investigate the properties of both gases and solids. There is also a theoretical program to calculate cross sections for atomic and molecular collisions and to study free-free transitions in the presence of intense laser fields (Gien). In 1979 an NSERC Strategic Grant was awarded to study coastal fog formations by laser reflection in conjunction with a program to investigate laser light scattering and nonlinear optics.

At St. Francis Xavier (Joshi, Wallbank), the activities include a range of spectroscopic studies of atoms and molecules from the infrared to the vacuum ultraviolet. The group is particularly noted for its very active international collaborations in the analysis of atomic spectra. Recent interest has focused on the spectra of highly ionized atomic states, free radicals and other transient species of chemical interest. The use of lasers as a tool in spectral analysis, photophysics and chemical physics is being actively developed. Work at St. Francis Xavier and Laval led to the first development of an electron energy selector in conjunction with a mass spectrometer by E. M. Clarke and co-workers in 1964. This was followed by the first cross section measurements for ion-molecule reactions in selected vibrational states. Particularly significant and pioneering work has also been done on the experimental observations of of multiphoton free-free transitions of electrons in the vicinity of atoms. This work requires the difficult task of simultaneously merging electron, atom and laser beams. The study of free-free transitions is being extended to the broader topic of laser assisted collision processes.

At the University of New Brunswick (Bao, Lees, Linton, Ross, Xu), research has developed from programs in optical spectroscopy, microwave spectroscopy and nuclear magnetic resonance, all begun in the 1960's. Current research particularly focuses on the laser spectroscopy of small molecules, and related energy transfer processes between molecules. Particularly significant measurements and theoretical analysis (Lees, Xu) have recently been done for the methanol molecule to obtain a better understanding of cometary processes. Recently, Ross has made important advances in the application of multichannel quantum defect theory to molecules such as H_2 and its mechanisms for dissociation and ionization.

2.2.5 Western Universities

In the prairie provinces, there are atomic and molecular physics groups at the Universities of Manitoba, Saskatchewan, and Alberta. At Manitoba, work has concentrated on mass spectrometry to study fundamental processes in desorption from surfaces (Ens), and various applications of laser spectroscopy and atomic beam methods to study molecular interactions and dynamics in dense gases through their influence on spectral line shapes and shifts (Tabisz), and electron scattering from excited states of atoms (Zetner). The latter involves difficult experiments involving a complete characterization of the coherence properties describing the scattering events, and it provides a sensitive test of theoretical descriptions.

Because of its northern geographical location, spectroscopic studies of the aurora and other atmospheric observations have played an important role in the historical development of atomic and molecular physics at the University of Saskatchewan. An older program of laboratory spectroscopy initiated by G. Herzberg before the Second World War has now been completely reoriented to atmospheric observations and analysis under the Institute of Space and Atmospheric Studies. This is further discussed in Sect. 6 (p. 33). Plasma physics research by Conway, Hirose, Xiao, and Smolyakov in conjunction with the STOR-M tokamak is discussed in Sects. 5.1 (p. 29) and 8.2 (p. 54).

The Alberta (Edmonton) group is largely involved with plasma physics, as discussed in Sects. 2.3 (p. 15) and 5 (p. 29). However, E. Pinnington initiated a very successful program of beam-foil spectroscopy in the late 1960's, and he pioneered the use of beam-laser interactions for the high precision measurement of atomic lifetimes and oscillator strengths, particularly those involving atomic ions of astrophysical interest. He continues to be an active contributor to this area, and plans to make extensive use of the recently constructed ECR source at Alberta. Also in Alberta, there is now a substantial general physics component at Lethbridge for the study of conformal field theory (Walton) and the classical-quantum correspondence in chaotic systems (Ali). On the experimental side, N. Moazzen-Ahmadi is contributing to our understanding of plasmas and gas discharges through his high resolution infrared spectroscopy of transient molecular species.

Similarly, the UBC program has a substantial plasma physics component discussed in Sects. 2.3 (p. 15) and 5 (p. 29). In addition, I. Ozier has a long-standing program for the high resolution measurement and analysis of the spectra of (a) diatomic molecules, (b) internal-rotor symmetric top molecules, and (c) molecular complexes. This involves much pioneering work of a seminal nature, such as the first measurement of the dipole moment of CH_4, and the first achievement of magnetic rotation spectroscopy in the visible with Doppler-free resolution. The application of this elegant technique to molecules such as I_2 allows one to probe the effects of electronic state mixing near the dissociation limit. Spectroscopic studies of internal-rotor symmetric top molecules provide valuable insight into the large amplitude motions of floppy molecules or molecular complexes, and the potential energy surfaces which govern their behaviour.

At Simon Fraser, the main area of concentration is in condensed matter physics. In General Physics, the theoretical work of L. Ballentine on quantum chaos and the classical-quantum interface, and more recently on the foundations of quantum mechanics has been particularly influential. The study of chaotic systems is a rapidly developing field with important applications in many areas such as quantum optics and mesoscopic systems. Other theoretical problems in nonlinear optics are being studied by R. H. Enns, such as interesting work on the existence of stable soliton-like "light bullets" in optically bistable media.

2.2.6 Government Laboratories

The major Canadian government laboratory conducting research in atomic and molecular physics is the NRC Steacie Institute for Molecular Sciences in Ottawa, created in 1990. This is in part an outgrowth of the former Herzberg Institute for Astrophysics founded by G. Herzberg and A. E. Douglas in 1948. The present activities of the Steacie Institute reflect the success of Herzberg in gathering about him a scientific staff of first-rate spectroscopists who, together with him, have made a large number of important contributions to the study of molecules of astrophysical interest.

The laboratory work includes a full range of high resolution spectroscopy from the microwave to the vacuum ultraviolet. The group has consistently worked at the forefront of the development and application of new spectroscopic techniques. It has to its credit the first observations of many spectra, and identification of new molecular species. A recent example is the first observation of the spectra of H_3 and H_3^+, and determination of their molecular parameters. This has led to a considerable amount of theoretical work on these fundamental systems. The molecular spectroscopy group, led by A. R. McKellar, continues to work on the infrared spectroscopy of weakly-bound astrophysical and atmospheric species, as well as laser spectroscopy of metal-containing molelcules, together with their theoretical interpretation (Bunker, Watson). Also at the forefront is the work of Madej on frequency standards, and of Gagné on laser cooling and the creation of a cesium optical fountain. This is a rapidly developing area that is otherwise under-represented in Canada.

Of great current interest at the Steacie Institute is the ultrafast phenomena group led by P. B. Corkum. With ultrashort laser pulses poised to enter the sub-femtosecond domain, optical methods now dominate the measurement of ultrafast phenomena in solids, liquids, atoms, and molecules. In molecular science, it is possible to measure the dimensions of wave-packets for dissociating molecules, and utilize wave-packets to control chemical reactions. This will open the way to a whole new field for the direct measurement and control of phenomena taking place on the time scale of molecular vibrations. This group has also received wide acclaim for their analysis and interpretation of atomic ionization induced by intense laser fields.

There is also some research related to atomic and molecular physics being done at the Defence Research Establishment at Val Cartier (DREV), and at the Chalk River Nuclear Laboratories. The work at DREV is mainly related to laser development and applications. They have made notable contributions to the development of the high power (TEA) CO_2 laser. The interest in atomic and molecular physics at Chalk River stems mainly from their work on the channelling of high energy ion beams in crystals, and the stopping powers of various materials. A knowledge of interatomic potentials is required for a detailed understanding of these processes.

2.3 Survey of Plasma Physics Programs

Plasma physics in Canada had an early start in the work done at the RCA Victor Research Laboratories in Montréal beginning in the late 1950's (associated with I. Shkarofsky, T. Johnston and M. Bachynski) and in the government Defence Research Laboratories at Val Cartier (both on plasmas formed around re-entry vehicles) and on ionosphere plasmas at the Defence Research Telecommunications Establishment. The university plasma physics research began with R. Nodwell's pioneering work using laser scattering diagnostics in arc plasmas, followed by the establishment of the first programs at the Universities of Saskatchewan (H. Skarsgard), Alberta (A. Offenberger) and Université de Montréal (G. Cloutier). After a heady period, including space plasma physics centred on the Alouette/ISIS series of topside sounder satellites, the space plasma physics remained with the Astronomy/Space Physics community (see Sect. 6, p. 33). At about the same time the hope arose of making significant Canadian contributions to the world effort on controlled thermonuclear fusion using magnetic confinement (MCF), in which domain there was already an interesting toroidal machine devoted to turbulent heating begun at Saskatchewan under Skarsgard.

In the early 1970's another way of attaining controlled fusion via implosions driven by laser beams, the so-called inertial confinement fusion (ICF) method, was unveiled. In the following 15 years or so, much excellent experimental work was done in Canada in this context using the long wavelength (10 micron) CO_2 lasers (usually in the Canadian-invented TEA form). This was accomplished at the NRC laboratories in Ottawa (Alcock, Richardson) and at UBC (Nodwell, Meyer), Alberta (Offenberger, Capjack) and at the newly established laboratories at the Université du Québec research institute INRS-Énergie at Varennes, directed by B. Gregory, with ICF work by Johnston and Henri Pépin. When it was determined that ICF laser drive required lasers with wavelengths (at the longest) in the half-micron range (for which laser systems are much more expensive than the Canadian CO_2 lasers), a short-pulse KrF laser (quarter-micron wavelength) program was initiated by Offenberger at the University of Alberta. However, funding for such a program of a stature relevant to ICF was not approved, and since then experimental laser-plasma research at Canadian universities has been redirected to other areas more peripheral to ICF (see Sect. 5.3, p. 31, and Sect. 5.4, p. 32).

Eventually a Canadian Fusion Program was indeed established in MCF in 1979 on a basis of equal provincial and federal funding. (The federal component came first through the National Research Council and then through the Atomic Energy of Canada Laboratories (AECL), who had previously funded research in plasma physics at UBC and Saskatchewan.) As well as the Fusion Fuels Technology Project in Ontario, a plasma tokamak project was rapidly established in Québec (calling on the talents of researchers at INRS and at the Université de Montréal together with scientists and engineers at the Hydro-Québec research laboratory at Varennes (IREQ)), all of which in 1985 came under the aegis of the CCFM (Centre Canadien de Fusion Magnétique). Since MCF research (Gregory and Barry Stansfield) had already begun at IREQ, and since Hydro-Québec provided the majority of the provincial funding, the Tokamak de Varennes (eventually about 35 professional scientists in all) came into existence in the High Power laboratory site at IREQ. Thus in the mid 1980's there was an era of considerable Canadian MCF development, an era which seems to be ending soon as federal funding for the Tokamak de Varennes is slated to end by April 2000. [However, the last word may not yet have been spoken since the huge International Thermonuclear Experimental Reactor (ITER) project may come to Ontario—an event which would very likely revive MCF in Canada.]

Much of the funding required for university fusion research (both in ICF and in MCF) came from outside the usual disciplinary Grant Selection Committee (GSC) process, through the NSERC Strategic Grants Energy Committee. When this fusion funding was terminated because "Strategic" came to mean "medium-term" commercial time scale (i.e. "tactical" rather than "strategic"), the NSERC-supported work in both MCF and ICF had to be phased out, except for some inexpensive collaborations in theory and modelling, and some experimental work performed in large foreign installations by Offenberger, Ng and Pepin. Thus, largely for financial reasons, most of Canadian plasma physics is perforce now in the process of evolving towards near-term applications (see Sect. 5.3, p. 31, and Sect. 5.4, p. 32). This is already evident in the diversity of occupations being found by the more recent Ph.D. students. As to quality, a significant indicator is publication in *Physical Review Letters*. In the 22 years from 1976 to 1996, the laser-plasma Canadian groups (5 groups totalling about 15 active faculty in all) contributed no less than 47 times to *Physical Review Letters*, a truly impressive output. Clearly the people trained in this way are both remarkably versatile and of very high quality. In the future, as the efforts of this talented pool of researchers perforce turn to more applied work, the applications of plasma physics to other areas of physics and to industry will become progressively more evident.

The themes of this general history can be discerned in the following paragraphs which summarize the activities of the various university groups participating in Canadian plasma physics.

University of British Columbia. In the early years, Roy Nodwell (now retired) began a program of plasma physics using arc plasmas diagnosed by ruby-laser Thomson scattering, under which many of the best people in Canada were trained. These included Barry Stansfield (who went directly to INRS), with the first laser beatwave experiment and Hector Baldis, who went on to NRC to do the best scattering experiments in the world elucidating many facets of laser-plasma parametric instabilities. Still others went to the Princeton Plasma Physics Laboratories, including Charlie Daughney and Jim Strachan. In subsequent work at UBC, Jochen Meyer refined the beatwave experiment and continued with the arcs. His most important work then followed with laser-generated plasmas and scattering laser diagnostics. By these means he became the world experimental authority on the two-plasmon instability. His work is still cited by the DuBois theory/modelling group at Los Alamos. Other early recruits were Frank Curzon, who trained many students on various plasma pinch machines, and Hannes Barnard, who worked on the related spectroscopic studies. When Andrew Ng arrived in 1980 from Alberta he initiated his own program using laser-generated strong shocks and has contributed significantly to the elucidation of the equation of state at high pressures, including recently deuterium at Mbar pressures. With the loss of Strategic Grant ICF funding, Meyer has put more emphasis on CO_2 laser short-pulse development and its use in channel formation in plasmas, while Ng has turned to a very fruitful collaboration with the Livermore Laboratory. Well before other physics-based commercial enterprises, one of the first physics spin-off companies in Canada was the Vortek company (Nodwell, David Camm and Gary Albach) with its water-swirl arc source of high-intensity light. Recent students from UBC and their current locations are listed in Table 1. This typifies the wide range of opportunities that is available to students in industry and government laboratories.

University of Saskatchewan. The Plasma Physics Laboratory at the University of Saskatchewan was founded in 1960 by H. M. Skarsgard. A plasma betatron originally designed to be a high current electron accelerator also found effective use as a turbulent plasma heating device because of its efficient electron and ion heating. Several original contributions were made by the team of Skarsgard and Akira Hirose (who came to the laboratory in 1971) with the device, including identification of a ripple-field-induced trapped electron instability, anomalous skin effect, thermal transport from the edge to core, and clear-cut observation of the predicted Budker-Buneman instability.

Tokamak research proper began in the late 1970's. The first Canadian tokamak, STOR-1M, was put into operation in 1983 and later replaced by a larger device, STOR-M. The research done on these machines established a strong Canadian presence in the world-wide effort to develop tokamak devices. Some of the principal contributions include the first demonstration of stable alternating current (ac) tokamak operation, Ohmic H-mode induced by edge heating, tangential injection of compact torus (C. Xiao), and development of microwave reflectometry for characterization of edge plasma fluctuations. Theoretical research conducted in the Laboratory [A. Hirose, O. Ishihara (now at Texas Tech University) and A.I. Smolyakov] covers tokamak stability and anomalous transport, particle diffusion in turbulent fields, nonlinear magnetic islands, and transport in nonequilibrium plasmas. Recently, programs of plasma sources for x-ray production and other industrial applications have been initiated. Many active plasma researchers were trained in the laboratory, including those listed in Table 1.

University of Alberta. A strong program of plasma physics related research was initiated in the 60's in the broad area of combustion and discharge plasmas. An immediate result of the work was the development of various forms of discharge and uv pre-ionized discharge CO_2 lasers (Offenberger, Seguin), and leading experiments on laser Thomson scattering from plasmas. A major program on the CO_2 Laser Heated Solenoid concept for fusion energy was carried out in the 70's and early 80's (Offenberger, Capjack). Another major program (Offenberger, Fedosejevs, Capjack) was one of the first in the world to study short-pulse KrF laser heating of plasmas, thereby demonstrating the effectiveness of ultraviolet wavelengths for fusion drivers. At the same time, some of the earliest measurements of Raman scattering and bandwidth control of Brillouin backscatter instabilities were

Table 1: Recent plasma physics students and their current positions.

Name	Organization	Position/field
	From University of British Columbia	
DaSilva, L.	Lawrence Livermore	X-ray laser expert
Celliers	Lawrence livermore	Laser-plasma research
Parfeniuk	Vortek	Mgr. Product Development
Pasini	Euratom Head Office	Scientific manpower coordinator
Elazzi	Alberta, Physics	Research assistant
Zhu	KREO Industries	Plasma applications
Laberge	KREO Industries	Plasma applications
McIntosh	DREV	Laser-plasma interactions
Bernard	NRC	Laser-plasma interactions
Popil	McMillan-Bloedel	Research supervisor
	From University of Alberta	
Boucher, C.	INRS/CCFM	Plasma research
Sarkissian, A.	INRS/CCFM	Plasma research
Zhang, L.	ALFT	Plasma research
Ishihara, O.	Texas Tech University	Faculty
Zhang, W.	JET	
Conway, G.D.	JET	
Mitarai, O.	Kyushu Tokai University	
	From University of Sasketchewan	
Tsui, Y.	Alberta	Research associate
Vick, D.	Alberta	Research associate
Al- Shiraida, Y.	Borealis Lasers	Laser development
Broughton, J.	Alberta Microelectronics Centre	Research mgr.
Gilesm R.	Bell Labs., USA	Senior scientist
Tighe, W.	Hughes Electron Dynamics Div., USA	Senior Scientist
Li, Y.	Columbia (E.E.)	Postdoctoral fellow
Pasternak, A.	JK Lasers (Lumonics), UK	Laser development
Fujita, M.	Osaka U., Inst. for Laser Tech.	Group leader
	From Université de Montréal.	
Boucher, C.	CCFM/INRS	Tokamak plasma, plasma discharge
Le Clair, G.	CCFM/MPBT	Tokamak plasmas
Chaker, M.C.	INRS	Laser-plasma technology
	From INRS-Énergie	
Ross	INRS	Ion beam and materials technology
Lafrance	INRS	Tokamak plasma, plasma discharge
Kieffer	INRS	Laser-plasma research
Lafontaine	INRS	Laser-plasma research
Novak	IREQ	Arc plasma physics and technology
Couture	IREQ	Tokamak plasma/electric car project
Boilly	IREQ	Surface and material science
McCarthy	Laval	Laser science
Parent	INO/NIO	Laser science and technology
Pelletier	McGill	Surface science
Nantel	U. Michigan Center for Ultrafast Optical Studies	
Whyte	General Atomic	Doublet machine
Boivin	UCLA and UC Irvine	
Ethier	Princeton (Suckewar)	x-ray laser group
Côté, C.Y.	Axis Inc.	President

demonstrated (Offenberger, Fedosejevs). On the theory side, Capjack developed unique capabilities for two-dimensional hydrodynamical simulations of laser plasma interactions, and Rozmus founded a strong analytic theory group, including major work on Coulomb kinetics, strongly coupled plasmas and modelling (with Capjack) of nonlinear effects (filamentation and SBS[2]) in underdense plasmas. The recent Ph.D. students still active in laser/plasma physics are listed in Table 1.

Université de Montréal. The program began in 1963 with work under Gilles Cloutier on the fundamental physics and applications of various discharge plasmas. This has been the focus of the research since then, rather than the controlled fusion program. In 1971 Jiri Teichmann started an ambitious series of experiments to understand wave-driven plasma parametric instabilities. In 1976 Michel Moisan initiated a very successful and still-vigorous program on surface-wave discharge systems. This work has developed many clients among chemists for chemical analysis. In 1989, Joëlle Margot began building larger-volume machines for wave-mode driven plasmas, with the aim of developing commercially useful plasma reactor systems with large throughput. This work includes full wave self-consistent modelling for these discharges to gain a better understanding of the processes involved. The recent doctoral students still active in plasma physics are listed in Table 1.

INRS-Énergie et Matériaux. The INRS-Énergie (now INRS-Énergie et Matériaux) is a graduate student research institute of the Université du Québec. Under its first director Brian Gregory, its aim from the beginning was to contribute to the world effort on controlled thermonuclear fusion using magnetic confinement (MCF). It soon became apparent that the two principal issues were the control of plasma instabilities, and the control of edge effects to prevent the plasma from damaging the walls and picking up impurities in the process. The INRS work has made particularly significant contributions to the latter problem. The early MCF work focused on the magneto-electric magnetic cusp machine KEMP (Gregory, Stansfield), and studies of first-wall damage effects in MCF reactors (Martel, Terreault). In 1979, the INRS MCF plasma effort (including as well Boucher, Marchand, Martin, Sarkissian, St. Jacques and Terreault) became part of the CCFM's Tokamak de Varennes program on tokamak plasma biasing, detached plasmas and related transport problems of divertor tokamak plasmas.

In addition to MCF, laser fusion work (ICF, directed first by Johnston and then Pépin) concentrated on electron transport issues both in experiment, using x-ray diagnostics (Pépin, Kieffer) to elucidate the anomalous transport of the hot electron fraction, and in theory through transport modelling (Matte, Johnston) and SBS theory. With the ICF switch to shorter wavelengths, Pépin led a successful transition towards applications, using the technology acquired in the ICF campaign. The principal applications success (Kieffer) has been in laser-driven short-pulse x-ray sources and collateral technology to develop x-ray streak cameras. Also, Chaker has achieved important success in the x-ray lithography and etching of materials using laser-plasma technology, including collaborations with Margot and Moisan at the Université de Montréal. Meanwhile, collaborations on theoretical problems relating to ICF are being maintained with major foreign laboratories such as Livermore and CEA-France. Topics include instability (SRS[3], SBS and filamentation) by Johnston, and transport problems, including normal Coulomb transport kinetics and more recently the effects of ion acoustic turbulence, by Matte.

The many students trained at INRS have had notable success in finding positions elsewhere. Some of the more recent graduates are summarized in Table 1.

[2]Stimulated Brillouin scattering from plasma electron density waves.
[3]Stimulated Raman scattering from so-called ion sound waves in a plasma.

3 Overview of Atomic and Molecular Physics

Atomic and Molecular science focuses on the properties of the common building blocks of the world around us—namely atoms, molecules and light—and on phenomena that occur in the ranges of temperature and energy that are characteristic of daily human activities. It is both an intellectually stimulating basic science and a powerful enabling science that supports many other important areas of science and technology. Students who graduate from this area of science acquire a broad range of knowledge and skills, making them valuable contributors to many areas of science and technology. Although lasers are considered separately in this report (see Sect. 4.1, p. 25, and Sect. 11.1, p. 78), they also form an important component of atomic and molecular science. Much of the high precision spectroscopic work (see Sect. 3.3, p. 23) involves lasers, and often they are used either to initiate or diagnose particular interactions. Application areas which benefit from the results of atomic and molecular science include industrial technology, manufacturing and processing, information technology, high-performance computing, communications, energy, global change, defence, medical technology, space technology and transportation.

3.1 Electron Collisions

Electron-atom collision phenomena lie at the heart of excitation processes in plasmas, and form an essential ingredient of models of plasmas and atmospheric phenomena. The study of these processes has been a major focus in Canada that has benefited historically through the presence of strong and active groups at Laval, UBC and Windsor. These have spawned much work elsewhere in the country and abroad. Both theoretical and experimental effort is well represented.

A wide range of processes has been investigated over an energy range which extends from meV to keV and higher. The driving forces in the field have been development of theory (with the understanding that experiment simply will not be able to supply the growing demand from industry for data on more and more exotic species and thus theory will have to!) coupled with the need for extension or revision of the existing data base on specific processes or interactions. Recently, studies of electron interactions with clusters and solids have forged new links with surface physics, leading to a better understanding of industrially important processes such as the plasma processing of surfaces.

In the area of atomic excitation, the Windsor work (McConkey) on the rare gases and atmospheric species is widely known and quoted. The experiments involve detection of emitted photons, sometimes their polarization, and sometimes in coincidence with the inelastically scattered electrons. Development of vuv polarization analysis technology was essential for this work. Zetner (Manitoba) studies superelastic scattering off laser-excited metal atoms to obtain similar basic information (amplitudes and relative phases) about the scattering process. McEachran and Stauffer (York) have developed a relativistic version of the distorted wave Born approximation which gives very good agreement with observations for a wide range of species and scattering parameters. The work on unstable atmospheric species (McConkey) is especially challenging because it requires the development of special sources which give workable concentrations of these atoms.

On the theoretical side, positron scattering has received considerable attention recently, particularly from the York group and Gien (Memorial). These developments have been motivated by recent experimental advances at Wayne State University, Detroit and elsewhere. Gien's extensive work on developments to the Glauber approximation have substantially improved agreement with experiment. Baylis (Windsor) continues his work based on the Dirac equation and is currently extending this to include inelastic as well as elastic scattering. Chidichimo (Waterloo) calculates electron-ion collision cross sections, particularly those of iron, at higher energies.

Marmet's (Ottawa) interests lie in high resolution electron impact ionization, carrying on the work he did at Laval and NRC. Wallbank (St. Francis Xavier) carries out experiments on electron scattering in a laser field, i.e. where both photons and electrons are involved in the collision process. His work has had a significant effect on theoretical developments in this area. Roy (Laval) studies inelastic scattering from both gaseous (mainly molecular) targets and surfaces. He continues the strong tradition at Laval for innovation in electron spectroscopy. Mitchell's (UWO) interests lie in low energy electron-ion collisions, particularly those of astrophysical significance. This work has been seriously hampered by lack of sufficient funding and has probably been transferred to France. McConkey (Windsor) has an extensive program to study dissociation of molecules and clusters using fragment-specific detection techniques.

In addition to the above, Canada has several other world-class activities in electron excitation which are not funded by a Physics GSC. Brion (UBC), Leung (Waterloo) and Hitchcock (McMaster) have made very considerable contributions to the AMO data base using higher energies where the electron can simulate a photon. Their work on oscillator strengths, molecular fragmentation, etc. complements that available from synchrotron sources. Sanche (Sherbrooke) has a unique and substantial effort involving electron-surface interactions.

A considerable fraction of the effort is driven by data demands from the broader scientific community, particularly industry. Thus low temperature plasma processing has stimulated a demand for cross sections involving etch-active molecules (Leung, McConkey); Stauffer was able to apply Monte Carlo modelling techniques to particle detector performance; Chang (McMaster) works directly on maximizing the efficiency of plasmas used to treat potentially hazardous waste materials from power plants, etc.

Essentially everyone has established links with colleagues in other countries working on similar problems. NATO grants, short- and longer-term visits to and from other institutes, membership of international projects etc., are all ways in which such collaborations are fostered.

3.2 Heavy Particle Collisions

Heavy particle collisions are prototypical of all chemical reactions and reactive processes. They give rise to a vast variety of excitation and ionization mechanisms whose detailed understanding is essential to models of the atmosphere and other chemical or plasma systems. Although some of the most interesting and challenging theoretical work has been done on these systems, only the simplest cases can be treated from first principles with any degree of reliability. For more complex systems, the interaction between theory and experiment is therefore particularly close as one must rely on various semi-empirical methods of analysis or approximation schemes.

The work here falls into two fairly distinct categories depending on the collision energy. On the one hand, a variety of experimental and theoretical techniques is being applied to a study of interparticle interactions at thermal or near thermal energies, while on the other hand, beams of ions or neutral atoms at much higher energies are used to probe their interactions with gaseous and solid targets.

Knystautas (Laval) irradiates a wide variety of materials with fast ions and by so doing alters their mechanical, optical, tribological, and electrochemical properties, thus producing novel "tailor-made" materials with many potential applications. Haugen (McMaster) studies beams of negative ions, in particular their excitation by multiphoton processes and usefulness in accelerator-based mass spectrometry. On the theoretical side, Dubé (Laval) is well known for his work on ion-atom and ion-solid interactions using distorted wave and other models. Chidichimo (Waterloo) studies proton-ion collisions as a complement to her electron-ion work mentioned previously. Horbatsch (York) has been developing large-scale computing techniques to investigate, for example, the ionizing power of ion beams or lasers as they interact with matter. Liu (Waterloo) also looks at particle surface interactions as well as collisional relaxation phenomena in molecular gases.

A number of groups studies interatomic interactions in gaseous targets using laser spectroscopic techniques. Among these are Atkinson, Krause and Czajkowski (Windsor), Tabisz (Manitoba) and Poll (Victoria). Information is obtained on fine-structure interactions, collisional energy transfer mechanisms, intermolecular dynamics, interatomic potentials etc. Theoretical work on these topics is done by Baylis (Windsor) and Tabisz. Studies of near-thermal interactions involving molecules trapped and aligned on surfaces are being carried out by Jensen (University of Northern BC).

3.3 Atomic and Molecular Spectroscopy

A large group of people, representing institutions across the country, and covering a broad range of topics, is involved in atomic and molecular spectroscopy. Absorption, emission and Raman spectroscopy are widely used, together with many different laser techniques. Apart from the fundamental interest in searching out new atomic and molecular parameters, energy levels, etc., considerable motivation is provided by the demands of industry and new technology.

A range of ingenious sources has been used depending on the particular project. Thus Knystautas and Larzillière (Laval), Haugen (McMaster), Rosner and Holt (UWO) and Pinnington and Kernahan (Alberta) use fast, often exotic, positive or negative ion beams to measure transition frequencies and lifetimes for excited states. They have collectively generated a huge body of data for plasma diagnostics and astrophysical applications. Czajkowski and Krause (Windsor) use supersonic nozzle expansions to produce molecules and clusters of heavy metals. Their analyses of the high resolution spectra obtained in these studies have greatly advanced our understanding of their extraordinarily rich structure and the underlying interatomic forces responsible for them. Hunt and Brooks (Guelph) use cryogenically cooled sources where excited species are trapped in a solid matrix such as solid hydrogen. The results provide a powerful means to probe the structure and excitations of the host matrix through its interactions with the trapped species. Gray (Guelph) studies the ultimate cluster, C_{60} and its derivatives, to unravel the unique properties of these fascinating three-dimensional structures. Reddy (Memorial), Joshi (St. FX), Lees and Linton (UNB), Hessels and van Wijngaarden (York), May (Toronto) and Tabisz (Manitoba) use a variety of other spectroscopic sources to perform measurements that are of fundamental importance to our understanding of atomic and molecular structure, or have direct applications to the study of plasmas and astrophysical sources.

An important part of the spectroscopic studies could be termed "laboratory astrophysics." For example, Larzillière and Holt have been the first ones to apply the method of fast ion beam laser spectroscopy (FIBRAS) to the study of molecular ions of atmospheric and astrophysical interest. Presently, the method is being applied with success by Larzillière to the photodissociation of molecules found in the ionosphere. No other method can compete with the level of precision obtained since the technique brings together high spectral resolution with high kinetic energy resolution of the photofragments. The studies led by Larzillière's group have found great interest with Hydro-Quebec and the company BOMEM who are funding in part the research. Hydro-Quebec is interested in the role of molecular ions in the atmosphere, and BOMEM (manufacturer of Fourier transform spectrometers) is developing a low pressure discharge for the production of optical emissions of molecular ions.

3.4 Other Atomic and Molecular Properties

These are many and varied, and they form an indispensable addition to the data base concerning how atoms and molecules interact with their environment. Negative ion resonance position and widths are readily accessed by electron spectroscopic techniques, as are autoionizing states. Data of this type are developed by Roy (Laval), Marmet (Ottawa) and McConkey (Windsor). Atomic and molecular lifetimes are essential for modelling astrophysical and other sources. These are measured using laser-induced fluorescence (LIF) and other techniques by Atkinson and Krause (Windsor), Rosner and Holt (UWO) and Pinnington (Alberta). Molecular fragmentation patterns are obtained by Enns (Manitoba) and McConkey (Windsor), thereby yielding unique insights into the geometrical structure of molecules, together with Franck-Condon factors and repulsive molecular potential energy curves. Of particular importance are the interactions of atoms and molecules with external electric and magnetic fields, as determined by their multipole moments and polarizabilities. In recent work, van Wijngaarden (York) has developed a new technique for the measurement of atomic polarizabilities for atoms in various excited states, yielding results of remarkably high accuracy.

3.5 High Precision Measurements and Theory

The ever-increasing capability of lasers for high precision measurements is opening exciting new possibilities for fundamental tests of atomic theory. The accuracy of these measurements for atoms such as helium and lithium can now be matched by essentially exact solutions to the Schrödinger equation recently obtained by Drake (Windsor) and his students. A comparison between theory and experiment then yields a well-defined residual difference attributable to higher-order relativistic and quantum electrodynamic (QED) effects, such as vacuum polarization and electron self-energy. Although these effects can be calculated to lowest order in the interactions, this does not provide sufficient accuracy to account for the residual differences. A computationally useful method to extend theory beyond the lowest-order term in systems more complicated than hydrogen does not exist. A solution to this challenging problem in basic atomic physics is currently under development by Drake and others. Until this is done, it will not be known whether or not theory and experiment are in agreement to the full accuracy of the measurements (0.1 parts per billion), even in as simple a system as helium. However, the unknown terms are sufficiently small that properties of the nucleus can already be extracted from their effect on atomic transition frequencies. This can now be done to better accuracy than is obtainable from high energy nuclear scattering experiments, and is opening the way to the study of exotic halo nuclei of lithium.

These theoretical advances are stimulating experimental efforts at various laboratories around the world, including Harvard, Darmstadt and Florence. In Canada, Rosner and Holt (UWO) extract QED shifts from very high precision measurements in helium-like ions. Hessels (York) is performing very challenging and interesting measurements sensitive to the elusive Casimir-Polder long-range retardation effect. Van Wijngaarden (Windsor) has developed a novel high precision test of QED effects by studying anisotropies in the radiation field following electric field quenching of metastable species. All of this work is pushing the state-of-the-art to its limits for the control and detection of photons.

4 Overview of Optics and Laser Physics

Optics is among the oldest and most fundamental of the physical sciences. The phenomenon of light provides the principal means by which humans perceive the external world. The unification of electricity and magnetism into electromagnetic theory by Maxwell represented one of the first grand syntheses of physics. The subsequent study of electromagnetic waves led to relativity, quantum mechanics, and our entire modern world of high speed communications.

Together with particle scattering phenomena, the interaction of light (photons) with matter provides one of the principal means for deducing the structure of matter and modifying its properties. At a fundamental level, the interaction of photons with charged particles is extraordinarily well understood within the theoretical framework of modern quantum electrodynamics. However, the collective interactions of matter with electromagnetic waves are far more complex, leading to new and unexpected phenomena, often with important scientific and/or commercial applications. Many of these flow from the invention of the laser and its unique capabilities for controlling and manipulating light. The ever increasing power and versatility of lasers continues to open exciting new areas for exploration and development.

The traditional strength of Canadian physics in classical spectroscopy left it well positioned to take rapid advantage of the possibilities provided by the advent of lasers. Lasers are now ubiquitous in Canadian laboratories, and many of their applications have already been discussed in Sect. 2.2 (p. 8). The intent of this section is to discuss those aspects pertaining specifically to lasers and optical devices. The research falls broadly under the categories of (i) development of lasers *per se*, and (ii) development of optical devices.

4.1 Laser Development

A world-wide research effort to advance the power and versatility of lasers shows no sign of abating and indeed is accelerating. One of the topics of current interest is the development of lasers or coherent sources operating in the x-ray region. An x-ray laser would make possible a new technology of "x-ray holography" and bring new advaces in medicine as well. Other major topics relate to the development of very high power (petawatt) lasers to explore the frontiers of light-matter interactions, and the use of laser diode technology and nonlinear optics to make compact, efficient tunable sources of picosecond and femtosecond pulses. Shorter pulses allow the dynamics of molecular reactions to be resolved down to the time scale of molecular vibrations—something which has heretofore not been possible. Higher peak powers reveal new phenomena under conditions where the atomic electrons are strongly driven by the electromagnetic field. Peak powers are entering an exciting new regime where the electrons are driven to relativistic velocities, resulting in what amounts to a desk-top "particle accelerator". These exciting developments are opening the way to dramatic new possibilities for applications in both science and industry, and it is important for Canada to be a part of it.

The development of new sources of coherent light in Canada has a good base but, in view of potential scientific breakthroughs and industrial interest, this base should be significantly enhanced. The four principal centres supported by NSERC are INRS (Beaudoin and Kieffer), Laval (Chin, Piché), the University of Toronto OLLRC (Herman, Marjoribanks, van Driel), and the University of Alberta (Offenberger). The INRS work is at the cutting edge of sub-picosecond laser development and ultrashort x-ray generation, as well as improvements to the peak powers of laser systems. At Laval, the group of S. L. Chin has developed three major state-of-the-art powerful laser systems: a TEA-CO_2 laser chain, a femtosecond dye laser chain, and Ti-sapphire laser chain. The last produces terawatt pulses that are among the most stable in the world, leading to new terratories for exploration in the interaction of high intensity laser pulses with matter. Piché is well-known for his work on understanding the mechanisms of mode-locked solid state lasers. His advances point the way to novel mode-locking mechanisms such as additive pulse mode-locking.

The OLLRC work is divided between the development of extreme ultraviolet or ultra-fast lasers for the microfabrication of photonic devices (Herman, Marjoribanks), and the development of new tunable, ultrashort pulse parametric oscillator/amplifier systems operating in the infrared, with eventual applications to the telecommunications industry (van Driel). In addition, van Driel's group is pushing the state-of-the-art for diode-laser pumping technology to develop novel, tunable, compact systems of interest to fundmamental research and Canadian Industry. Both programs are very active and productive in a rapidly evolving and competitive field. At Alberta, important progress has been made in the development of high-power KrF lasers, and their application to "fast ignitor" experiments for controlled fusion. This work also involves strong collaborations with high-power laser programs at the Lawrence Livermore National Laboratory (U.S.) and at Oxford.

4.2 Optical Devices and Nonlinear Optics

The field of fibre optics has recently exploded in importance to cover lasers and optical devices, as well as their original use as passive transmitters of optical signals. The key discovery was that doping the glass in an optical fibre with erbium or other rare earth ions could turn the fibre into an optical amplifier. This and other related optical devices have a broad range of new applications that is revolutionizing the communications industry. Current research on fibre switches, fibre modulators and fibre isolators is leading to all-optical computers and communications systems with much higher intrinsic speeds and carrying capacities than are currently possible. The control and manipulation of photons by optical devices is now called *photonics*, in analogy to conventional electronics.

One of the strongest concentrations of research on optics, optical devices and nonlinear optics in Canada is at Université Laval. The study of optics has played an important role at Laval since the early 1960's. In 1968, a group led by A. Boivin formed the Laboratory for Optics and Hyperfrequencies (LOH) with NSERC support, and in 1974, this evolved into the Laboratoire de Recherche en Optique et Lasers (LROL) with the eleven professors. By 1984, the rapidly growing importance of optical oscillators led to the establishment of an NSERC Industrial Chair in Optical Telecommunications, now filled by Prof. Michel A. Duguay in Electrical Engineering. In 1989, 14 Physics and 4 Electrical Engineering faculty members joined forces to form the Centre for Optics, Photonics and Lasers (COPL). More than 160 students have received a Masters or Ph.D. degree in the last 10 years.

The various research programs of COPL can be broadly classified under:

- Optical Communications (Michel A. Duguay, Sophie LaRochelle, Leslie A. Rusch, Michel Tetu and Pierre Tremblay). Topics include microwave oscillators sychronized by an indirect optical injection, semiconductor optical amplifiers, distributed feedback lasers, optical fibres and optical waveguides, arrow waveguides, and fibre lasers.

- Lasers and guided propagation (Pierre-André Belanger, Nathalie McCarthy, Michel Piché, Réal Tremblay, Réal Vallée and Alain Villeneuve). Topics include lasers, laser cavities, high power infrared short pulses, fibre sensors, femtosecond and picosecond optical parametric oscillators, optical components based on AlGaAs materials and optical fibres, etc.

- Optical materials (Marguerite-Marie Denariez-Roberge, Tigran V. Galstian, Roger A. Lessard). Topics include modification of optical materials by ionic implantation, photochromism and photorefractivity in polymer based materials, materials for optical memory, real-time holography and polarisation holography, liquid crystal-based materials, second and third harmonic generation in polymer materials, and holographic optical elements.

- Laser-matter interacation (S.L. Chin). Topics Include propagation of ultra-short laser pulses in liquid and gases, very high harmonic generation in molecular and atomic gases, dissociative ionisation of simple molecules with a high power laser, and trapping and non-sequential ionization of atoms and molecules in an intense femtoseceond laser field.

- Image sciences (Henri H. Arsenault, Ermanno F. Borra, Claude A. Delisle and Yunlong Sheng). Topics include diffractive optics, construction and testing of large diameter (2.7 m) parabolic liquid mirrors for observational astronomy, optical design of an optical corrector for a fixed telescope, optical information processing, wavelet transforms, filters and filtering, and neural networks. (Roger A. Lessard): computer generated holograms, holographic optical elements and holographic applications.

LROL and now COPL has been particularly active in holography and optical image processing for many years and has published many influential articles in this area.

The laboratory is well equipped with a wide variety of high-power excimer, solid sate, gas and dye laser systems, as well as ultra-high vacuum film deposition equipment and computerized image processing systems. The spin-off companies Holospectra, Laser Inspeck, and Lasiris have been formed by R. Lessard, together with Laval graduates, to exploit the commercial applications of optical devices. In addition, the very successful company EXFO is discussed in Sect. 10.2 (p. 72).

The liquid mirror project (Borra) mentioned above is attracting considerable international attention as a method to produce very large diameter telescopes at low cost that are particularly well suited to broad surveys of the sky. It has now advanced to the stage of joint observational programs with UBC to detect faint objects for cosmological applications, and with UWO to monitor the upper atmosphere using Lidar methods.

Several other smaller programs should be added to the above. In Québec, the group of Bertrand, Gagné, Lacroix, and Najafi at the Ecole Polytechnique is conducting research on a variety of topics related to integrated optical devices and nondestructive methods of optical control, as well as applications of the nonlinear Kerr effect in optical fibres. M. Fontaine at the Université du Québec à Hull provides theoretical support for the development of optical devices by her numerical simulations of polarization effects in optical fibres and optically active films deposited on semiconductor materials.

In Ontario, the OLLRC is the most active centre for the development of optical devices and encompasses reserachers in engineering, physics and chemistry. Besides the work mentioned above, particularly worthy of mention is the work of Measures who pioneered the application of fibre optics to structural sensing, and was among the first to develop fibre optic damage detection systems (see Sect. 10.2, p. 72). Also, Smith has demonstrated a nonlinear coupler switch capable of substantially complete all-optical switching at sub-picosecond rates, dubbed the "world's fastest switch".

At Wilfrid Laurier University, Lit continues a long line of prominent research on fibre and integrated optics. Among his outstanding achievements was a patented integrated wavelength division multiplexer for upgrading optical fibre communication systems. Most recently, one of his erbium-doped fibre lasers has been developed and sold in America and Europe by MPB Technologies of Canada. Also at WLU, Wartak has established a program for the theory and characterization of quantum-well lasers in collaboration with Nortell Technology. The high gain and line width enhancement factors that can be achieved with these devices give them important applications in telecommunications.

In the Maritimes, X. Bao at the University of New Brunswick is developing optical cables for long distance communications, temperature and strain sensing. She is the first to have used the Brillouin scattering loss mechanism for the distributed sensing of strains, and has developed the longest distributed temperature and strain sensors. In addition to NSERC, this work is strongly supported by NBTel.

The theoretical work of Enns at Simon Fraser University on nonlinear optics has already been discussed in Sect. 2.2.5 (p. 13).

4.3 Applied Optics in Government Laboratories

In addition to university-based research in optics, there are two laboratories funded in part by the federal government, the Communication Research Laboratories in Ottawa, and the National Optics Institute in Québec, which are doing world-class research on applied optics.

The Communications Research Laboratories conducts research on photonics. Particularly significant is the research group of K. O. Hill. His group produced the first c.w. Raman and Brillouin lasers. Their research on fused biconcical tapered fibre couplers led to devices that are now used throughout the world under a Canadian patent. Hill's group is particularly famous for the discovery of photosensitivity in optical fibres. They found that standing electromagnetic waves can produce local modifications to impurities in the optical fibre, resulting in the creation of a periodic optical fibre grating (Hill grating). This development has led to a world-wide research effort to utilize this technology in optical communications, as optical fibre sensors and as laser controllers. As one example, optical fibre gratings have direct application to the spacial separation of multiplexed signals carried by different colours in a single fibre.

The mission of the National Optics Institute is technology transfer from academia to small or large business. The Institute has developed many products which are marketed by local or national industries. Examples are variable reflectivity mirrors for high-power lasers, diffractive optics components (beam-splitters for high power lasers, beam samplers, imaging systems, components that transfer a gaussian beam on a ring image, etc.), pulsed fibre lasers for pollution monitoring, specialty fibers, arrays of bolometers, and fibre sensors. Some of these products have become international trademarks of excellence. For example, the variable reflectivity mirrors are now a standard element of any high-power laser that is considered to be competitive on the market. These mirrors have been entirely developed in Canada.

In summary, the strong Canadian presence in optics, lasers, and optical devices is a natural outgrowth of the traditional strength in atomic and molecular physics. Lasers and other optical devices provide the primary means for observing atomic and molecular processes, and in turn, a better understanding of the interaction of light with atoms and molecules aids in the design and construction of better lasers. The two go hand-in-hand in the study of surfaces and the development of new photonic devices of great potential importance to the telecommunications industry. In addition, medical applications of lasers are of rapidly growing importance, and their applications to plasma physics and atmospheric science are firmly established.

5 Overview of Plasma Physics

Since the last century, spectroscopists have studied the light emitted by the arcs, sparks and glows produced by an electrical discharge through gases. The results of these studies laid the foundations not only for quantum mechanics and the modern quantum theory of matter, but also for a whole host of applications in the lighting industry, electronics, and laser design. It soon became apparent that the gas in a conducting state represents a new form of matter, called a plasma, whose properties are determined in part by the presence of free electrons and ions. In fact, a substantial fraction of the matter in the universe exists in a plasma state, such as the sun and the upper atmosphere of earth (the ionosphere). Since the 1950's, interest in plasma physics has grown rapidly because of its applications in astrophysics, electrical engineering, laser technology, geophysics, aerodynamics, and especially in controlled thermonuclear fusion. We have now come full circle in that the light produced by high-power lasers is so intense that the gas through which it passes itself is ionized to become a plasma, and the electric fields are so large that the free electrons acquire relativistic velocities.

The study of plasmas is by its nature interdisciplinary. An understanding of plasma processes requires a vast wealth of basic atomic and molecular data on collision cross sections and radiative transitions. Lasers and optical devices are essential in creating plasmas and observing their properties. The techniques of statistical physics are required to account for their microscopic properties, while their large scale collective behaviour (such as plasma oscillations) can usually be understood in terms of classical physics. Thus, nearly all the topics covered by General Physics (GSC-29) are involved. Applications to atmospheric/space science and to cosmology further broaden the range of topics to cover all of GSC-29, as well as GSC-17 (atmospheric/space science).

The plasma physics activity in Canada can be naturally summarized under four headings: Magnetic Confinement Fusion (MCF), Inertial Confinement Fusion (ICF), Laser-Plasma Interaction (LPI) and Plasma Applications Research (PAR). In reaction to budgetary pressures, there has been an accelerating flow from the first two large-scale and long-term activities (MCF and ICF) to the last two modest-scale near-term activities (LPI and PAR). Each of these is discussed in turn in the following subsections.

5.1 Magnetic Confinement Fusion (MCF)

The basic idea of MCF is to confine the charged particles of a plasma within a "magnetic bottle" while they are heated to sufficiently high temperature for fusion to take place when the particles collide. The most promising candidates are toroidal devices called tokamaks. In tokamak machines, a plasma current is induced around the axis of a torroidal vessel by the sudden pulsing of an external magnetic field. The current in the plasma causes a poloidal magnetic field which together with the externally applied magnetic field confines the plasma. The major obstacles to be overcome are plasma instabilities under the required conditions of high temperature and pressure, and energy loss mechanisms due to impurities and interactions with the walls.

The two principal facilities for MCF research are:

- the Federal/Québec co-funded Tokamak de Varennes, which is run by the CCFM (Centre Canadien pour la fusion magnétique),
- the NSERC-funded Saskatchewan STOR-M tokamak.

Both of these are under severe funding pressure. The NSERC-funded researchers are as follows:

- CCFM: Marchand, Ross (partial), Shoucri, Terreault (partial), Gregory, Stansfield, Sarkissian (all INRS), and MacLatchy (Acadia),

- STOR-M: Hirose, Smolyakov, Xiao,
- FFTP (Fusion Fuels Technology Project): Stangeby and Pitcher (both UTIAS, i.e. University of Toronto Institute of Aerospace Studies).

The impact of the MCF work at CCFM has been significant and has merited distinct sessions (poster and oral) at the annual meeting of the Division of Plasma Physics of the American Physical Society, with particular emphasis on the excellent work on plasma biasing effects on transport, divertor plasma physics and lower-hybrid frequency current drive and heating. Unfortunately, at this point it is difficult to say whether this activity will continue in the face of what is apparently part of the "collateral damage" of the Federal Government's drastic reductions of the AECL budget. The particular efforts of Terreault and Ross on characterizing plasma effects on divertor and limiter materials are being re-directed to other non-MCF applications, as are, in part at least, the plasma expertise of Gregory, Stansfield and Sarkissian.

The much smaller STOR-M tokamak team has also had a noticeable impact. Although their turbulent heating is not currently fashionable, the compact plasma torus injection work has been excellent. Unfortunately the excision of fusion-related research from the Strategic Grant area means that STOR-M funding is also now below critical. In sum, failing unforeseen but desirable developments, the excellent Canadian MCF work (considering the funding level) is in danger of coming to a premature and unfortunate end.

5.2 Inertial Confinement Fusion (ICF)

At present the Canadian ICF work (Johnston, Kieffer, Matte and Pepin at INRS; Capjack, Fedosejevs, Offenberger, and Rozmus in Alberta; and Ng at UBC) involves international collaborations, either in theory/simulation (Johnston, Matte, Rozmus and Capjack) or in experiment collaborations (Pepin, Offenberger, Fedosejevs). This mode of operation is the result of the high cost of relevant experimental facilities and (to a lesser extent) to the requirement of super-computing power for the relevant simulations. To reprise the history briefly, the earlier significant impact from Canadian experiments (many in the now-defunct Plasma Physics group at NRC) had been based on the relatively inexpensive long-wavelength carbon dioxide laser. This impact declined steadily (despite some persisting use in "scaling" experiments) when it became clear that ICF laser drivers should have relatively short wavelengths to avoid electron preheat problems from various plasma instabilities. Since this requires enormous and expensive glass lasers, purely Canadian experiments, such as those of Ng and Fedosejevs, became marginal, except to the extent that they provided some confirmation of particular physics issues. Experimentalists who wish to stay relevant to ICF must now go to the appropriate foreign facility, which in North America means the Nova laser at Livermore. Offenberger has undertaken to work at Livermore on their ICF Fast Ignitor effort (see following paragraph), while Ng has joined the Cauble team doing a large-scale version of his laser-driven shock attack on the high pressure equation of state (EOS), and apparently is to head a 1997 university project on Nova on the same topic. As pressure mounts to broaden the base of Canadian funding (especially in the face of ICF exclusion from the NSERC Strategic Grant program) the other researchers are tending to evolve towards more short-term research in fields closer to industrial applications.

A recent ICF concept (Fast Ignitor) has generated a considerable amount of excitement on the interaction with plasmas of extremely intense laser beams (such that the electron oscillation momentum is relativistic) and their penetration through plasmas well over the usual critical density. There has been previous work, mostly in the U.S., aimed primarily at possible future particle accelerators based on underdense plasmas. Offenberger was involved in a pertinent experiment in his experimental collaboration at the British Rutherford-Appleton Laboratory, but that seems to be the extent of any Canadian involvement, probably because there is no source of funding for research into exotic particle accelerators. Meyer is planning to use a short-pulse CO_2 laser to investigate the physics of ponderomotive channeling, albeit at a wavelength far larger than those used in ICF. To date, Pepin has collaborated with a penetration experiment in France (C.E.A., Limeil-Valenton), Offenberger is currently closely involved in the Livermore Fast Ignitor experimental program, and Johnston is involved in the associated theory/simulation studies. However, there is no other Canadian activity in the Fast Ignitor. It can therefore be termed a fascinating idea with a modest Canadian content. Serious experimental Fast Ignitor experimental work probably requires at least 30 TW of picosecond duration power, and Livermore's lasers are 100 TW and 1PW (1000 TW)—far more than one might ever expect in Canada.

5.3 Laser-Plasma Interactions (LPI)

To a considerable extent, the LPI work has been a re-orientation of work originally pertinent to ICF. Five basic lines can be distinguished: (i) equation of state(EOS)/transport (Ng, Fedosejevs, Rozmus and Matte), (ii) x-ray lithography (Pepin, Chaker, Kieffer and Fedosejevs), (iii) specific laser ablation applications (Chaker, Moisan and Fedosejevs) (iv) short-pulse x-ray sources (Kieffer, Matte), and (v) picosecond-pulse laser-produced very long plasma columns (Pepin, Kieffer and Johnston) and (vi) coherent xuv radiation source development, by means of high-harmonic generation or recombination laser schemes (Offenberger, Burnett, Capjack).

The EOS/transport activity (i) can be termed as nearly pure plasma physics with a weighting towards topics of interest to ICF, and, in the future to compressed matter of astrophysical interest. Ng's excellent work on measuring EOS at the high pressures from laser-driven shocks now being exploited at Livermore (see Sect. 5.2, p. 30), will be applied for astrophysics, while femtosecond heating experiments allow an attack on the problem of degenerate plasmas at more normal densities. The x-ray lithography effort (ii), after an excellent start on matching x-ray source characteristics and mask components, is somewhat on the back burner while the current industrial investment is being made at longer wavelengths in the visible and near-visible range. In any case, for industrial applications of laser x-ray sources, one must wait for necessary laser improvements in repetition rate and average power. Once these improvements have been achieved, dramatic new possibilities will open up for the applications of these devices.

Laser ablation work is being pursued for specific applications (iii) such as deposition of thin films of various materials (sometimes in association with an HF discharge plasma) (Chaker, Margot and Moisan), and use of a novel concept to reduce debris deposition by the magnetic guiding of the laser plume (Fedosejevs). Accelerating effort is also being placed on two dramatically new projects: (iv) short x-ray pulses from irradiation by short laser pulses, and (v) the interestingly long plasma columns and their use in high-voltage breakdown. In the first of these projects, the short-pulse laser-driven x-ray source development, the importance of negligible laser prepulse and strong light pressure has been shown (Kieffer) to be vital to keeping the plasma density high to allow rapid decay of the x-ray emission. [This work is also closely linked to the commercial (French-U.S.-INRS) development of a sub-picosecond x-ray streak camera (Kieffer).] In fact the smaller x-ray source size resulting from the use of short pulses has resulted in a U.S. NIH-funded collaboration (INRS and SUNY Health Sciences Center at Syracuse) to explore the angiographic diagnostic possibilities of these smaller sources. In the last project, the interestingly long plasma columns and their use in high-voltage breakdown, there is a significant NSERC University-Industry (Hydro-Québec and INRS) project (Pepin, Kieffer and Johnston) to push this towards very practical use in industrially relevant cases. This by no means exhausts the impressive list of Canadian facilities or projects.

Besides those implicitly mentioned at INRS and at Hydro-Québec's IREQ Laboratory, and at NRC (see Sect. 2.2.6, p. 14) there are also the following: at Alberta, Fedosejevs' subpicosecond 0.5 TW KrF laser (xuv sources and nonequilibrium ionization), at Toronto, Marjoribanks' all-Nd picosecond TW laser (harmonics from solids and vuv), at Laval, Chin's Ti:sapphire 200 femtosecond 2 TW laser (ionization, harmonic production) and, at Waterloo, Strickland's high-repetition-rate sub hundred femtosecond laser (molecular dynamics and control). Clearly there exists an excellent network on which to construct a significant Canadian effort in this exciting field. The advent of high-power femtosecond laser pulses has opened up a new era of very nonlinear interactions and the generation of harmonic radiation stretching into the xuv range, and also (vi) the possibility of pumping xuv recombination lasers. These new areas are being pursued by Offenberger, Burnett and Capjack at the University of Alberta.

5.4 Plasma Applications Research (PAR)

This heading includes applied plasma physics research (i.e. client-oriented), which does not directly involve lasers and which does not fall under the preceding sections. The principal topic is the physics of what are termed "plasma reactors". In particular the Montréal-INRS collaboration (Margot, Moisan, Chaker, Johnston and Matte) has mounted a major ongoing effort aimed at improving the understanding, modelling and performance of high-frequency plasma reactors. Modelling of weakly ionized plasmas in connection with chemical analysis is the theme of an ongoing collaboration [Margot, Matte and Hubert (Chemistry, Montréal)].

Finally, Terreault, Paynter and Ross at INRS and Knystautas at Laval are involved in the characterization of the results of plasma surface processing and of low-voltage ion beam implantation. While this is not strictly plasma physics as such, it represents an important application of the techniques of both plasma physics and atomic and molecular physics to the creation of new materials with unique mechanical and electro-optical properties. It is an interdisciplinary area with potentially great commercial applications.

5.5 Links with other Themes of General Physics

It is clear from the above that the links between plasma physics and the other topics associated with General Physics (GSC-29) are very close. In particular, laser physics/spectroscopy/optics and atomic and molecular scattering have direct applications to much of the plasma physics work. Apart from the fact that laser-plasma physics uses lasers as active agents [ICF glass lasers, chirped-pulse-amplified lasers for extremely high power sources], lasers are routinely used for diagnostics, sometimes in very sophisticated ways [Thomson scattering subtleties and ion velocity measurements in plasma reactors by laser-induced fluorescence (LIF)], passive spectroscopy has always been an essential diagnostic tool at wavelengths from the visible to the x-ray regions. Certainly the MCF community has been an insatiable consumer of a remarkable variety of scattering cross section data, especially as regards impurities, while the production of extremely high power neutral beams (admittedly not in Canada) from useful ions has been an essential MCF activity. In the same vein, both ICF and the international effort at producing affordable x-ray lasers implies a very close synergy between plasma physics, scattering and radiation. In connection with work using intense laser pulses in gas targets, recent topics of particular interest are high-field ionization and the subsequent electron behaviour, especially for the experimentally relevant plane-polarized case, and emissions at high laser harmonics in plasmas.

6 Overview of Atmospheric and Space Physics

The Canadian effort in space and atmospheric physics can be readily traced to the obvious impact that climate has on our everyday lives and the fact that auroral displays are seen by every Canadian at least once in their lifetime. The initial pioneering work in this latter area was done at the University of Saskatchewan and at the University of Toronto, where J. C. McLennan was able to identify the source of the green auroral emission. This work was expanded through the second International Polar Year in 1932-33 and the International Geophysical Year in 1957. A great number of the advances in our understanding of the aurora and the nature of its spectrum have been led by Canadian scientists, many of whom have been trained at the University of Saskatchewan. These scientists have gone on to be leaders throughout the world in atmospheric and space physics.

Unfortunately, as we have developed our understanding of the space environment, we have also recognized that Canada simply does not have the resources to investigate all aspects of solar-terrestrial relations, from the sun through to the final dissipation of energy in the terrestrial atmosphere, nor for extensive studies in planetary atmospheres. Thus, while by its very nature the NSERC funded program is quite diverse, Canadian scientists have often chosen to direct their efforts into those particular areas where they have made major international contributions.

The leadership of Canada in auroral imaging, through the Viking and subsequent missions, has allowed many new international imaging missions and, almost without exception, Canadian scientists are invited to play a leadership role in any new international imaging missions.

The development of the wind imaging Michelson interferometer (WINDII) has been pioneered by Canadian scientists and follows on the initial ground-based work of G. G. Shepherd when he was at the University of Saskatchewan. The Michelson interferometer that is presently flying on the UARS spacecraft is providing unparalleled new information. This class of instrument also represents a major technological advance and Canadian scientists are leading the world effort in extending the concept to other spectral regions.

Canadian scientists studying the airglow provided the first measurements of ozone throughout the mesosphere, and the existence of the second ozone layer was first reported by a team from the University of Saskatchewan. The techniques pioneered by those scientists have already been used to provide global maps of mesospheric ozone and new Canadian developments in the application of airglow tomography are in the forefront. Canadian researchers have also been leaders in the identification of ozone depletion in the arctic.

Particle and field studies have continued and expanded from the world's first radar auroral observations; the present work with the SuperDarn system is maintaining Canadian scientists at the leading edge. However, Canada is much more than a mere supplier of observational data. We have some of the world's leaders in the theory of space plasmas and the application of knowledge to improve our understanding of the environment. Thus, although Canada is limited in its scope of atmospheric and space physics, the achievements by Canadian scientists are at the forefront of the world's efforts this work.

6.1 Principal Centers of Activity

Atmospheric and Space Physics in Canada has benefited from the National Centres of Excellence Program. Leroy Cogger at the University of Calgary was the Executive Director of the NSERC-sponsored Centre of Excellence—the Canadian Network for Space Research (CNSR), the executive offices of which were in the Space Research Centre of the University of Calgary. This program enabled the establishment of very major research initiatives at a number of universites. Space and Atmospheric Research has also benefited from the direct support of the Canadian Space Agency with both its vision statement, the Magog document, and important space instrumentation.

University of New Brunswick. The activity here is centered around the Industrial Chair (sponsored by Com-Dev) in Space Physics. It is aimed at making new high resolution EUV solar spectra. This work was transferred from Stanford to UNB by Gethyn Timothy, the project PI. A new concept study to investigate the possibility of solar spectral tomography is also being undertaken. The University have also expanded the number of faculty involved in Space Physics with the appointment of A. Hamza, a space plasma theorist from UWO. It is significant that the Space Physics discipline was an area actively pursued by the provincial government as it was seen to have important economic benefits.

University of Toronto. The activity here is centered around two major projects. The MOPITT (Measurement of Pollution in the Troposphere) instrument, which is an IR radiometer that will fly on the NASA EOS Mission (PI Jim Drummond), is a major undertaking for Canada that will provide data of immediate importance to our understanding of the lower atmosphere. The second major activity is the Middle Atmosphere Model (MAM) (PI T. Shepherd), which is a large GCM that will include a detailed chemical and radiation code. This model is presently being extended in altitude so that it is appropriate to the observations expected from the Odin/OSIRIS satellite. There is also a collaboration with the Odin/OSIRIS program.

York University. The space activities here were initiated with the establishment of CRESS (see Sect. 2.2.1, p. 9). The work is is now led by G. G. Shepherd, the WINDII PI. This extremely successful space-borne imager has been in orbit since September 1991 and uses the Doppler shift of the observed airglow emission to measure winds in the mesosphere. An important feature of the instrument is that it has sufficient resolution to accurately remove the Doppler shift due to the satellite motion to determine the wind speed. The WINDII observations have been used in very novel and unexpected ways to identify polar stratospheric clouds, those associated with ozone depletion, and polar mesospheric clouds (noctilucent clouds) which are possibly associated with global warming. At present the large data-base generated by WINDII is being investigated for solar cycle effects. The WINDII experiment has also spawned an associated ground-based program, much of which is located at the Eureka Observatory. This observatory is an outcome of the national Centres of Excellence program. Instrumentation for ground-based geospace observations has been developed at York and ISTS, the provincial Center of Excellence, and makes complementary measurements. The entire WINDII program and its associated researchers involves about twenty people at York and elsewhere in Canada. A second program at York involves the use of lidars for active sounding of the atmosphere. This work, which includes a very large industrial component, is led by A. Carswell. There is also a major rocket experiment effort underway (PI I. McDade) that is intended to improve our knowledge of the oxygen airglow and so permit improved remote sensing. Other researchers at York are involved with the MAM model, with the Odin/OSIRIS imager, with collaborative research programs with AES, and with space plasmas.

Trent University. There is a small program at Trent (PI W. Evans) that is associated with WINDII and with the measurement of greenhouse gas effects. Much of this work is actually undertaken at York through an adjunct appointment.

University of Western Ontario. UWO has a vigorous research program in the physics of the middle atmosphere and of the ionosphere. This is evidenced by the fact that several state-of-the-art instruments (many of which are legacies of the Centers of Excellence program) have been developed and refined right there at UWO; some of these instruments have even been marketed commercially. These instruments are based either on the scattering of radio waves (Hocking, MacDougall and Moorcroft) or on optical techniques (Lowe and Sica). There is also a strong theoretical and modeling component (St-Maurice) in space plasma physics and in neutral gas turbulence in the middle atmosphere (Hocking).

The atmospheric research at UWO is directed toward an understanding of the role played by small to medium scale processes on the dynamics and energetics of the atmosphere. Examples include the versatile VHF CLOVAR radar and its Resolute Bay counterpart, which are able to monitor clean air turbulence in the troposphere with unprecedented accuracy, while simultaneously recording so many meteor echoes near 100 km altitude that the radar can be used to find meteor shower remnants as well as deduce the neutral temperature and the wind profile of the atmosphere in that region. The UWO Purple Crow lidar with its unique liquid mirror telescope design and an array of UWOME Michelson interferometers are able to monitor the passage of gravity waves and the temperature perturbations that accompany them. This Michelson interferometer work has a close association with the WINDII program. A novel implementation of the Brewer spectrophotometer also uses star light to allow for the detection of ozone over the polar regions in nighttime conditions.

The ionospheric researchers tend to focus on the dynamics of auroral processes. The portable and versatile CADI (Canadian advanced Digital Ionosonde) has been deployed over several high latitude locations to provide important information not just about the ion densities in these regions, but also on the formation and evolution of large scale structures ("blobs"), as well as on the circulation pattern over the polar cap, and on the dynamical interaction of atmospheric gravity waves with the ionosphere. The MIDAS receiver unit is a unique portable radar receiver system that has been used to process radar data bistatically from the Millstone Hill observatory in Massachusetts, using the Algonquin radar dish. The group is also part of the Canadian SuperDARN team (PI G. Sofko, University of Saskatchewan). It has so far been focusing on understanding the origin of the radar echoes and on the interaction of gravity waves with the ionosphere using the additional clues provided by a strategically located CADI instrument. The theoretical efforts are directed, at least in part, toward understanding the (usually nonlinear) dynamical plasma processes that affect the ionosphere, and modify its composition and transport processes. Indeed, understanding nonlinear plasma processes is key to understanding the way by which the ionosphere is coupled to the magnetosphere, and ultimately to the solar wind.

Other Ontario Centers. The university atmospheric and space research in Ontario is strongly influenced by the proximity of AES and the provincial Center of Excellence (ISTS). There is a very strong collaborative program particularly in the development of new space-borne instrumentation and in large scale modelling efforts. There is also a significant space research effort at the Communications Research Centre under the leadership of Gordon James.

University of Saskatchewan. The research program here, which is organized within the Institute of Space and Atmospheric Studies, contains major efforts in each of the three primary areas associated with space and atmospheric research. The Canadian part of the SuperDARN[4] effort is led from here. The aim is to make a map of the convection or electric field activity in the F-region of the auroral zone and polar cap. Each pair of the six SuperDARN radars can map out an area

[4] SuperDARN is an international program involving six HF Doppler radars in each hemisphere. The Canadian contribution is led by G. Sofko (Sask.), and involves scientists at the University of Saskatchewan (Koustov, Hussey, Koehler), University of Alberta (Samson), University of Western Ontario (Moorcroft, St.-Maurice, MacDougall) and University of New Brunswick (Hamza).

of over 3 million km^2. As a result of combining these maps for all of the international radar pairs, the large-scale dynamics of magnetospheric convection and field-aligned currents can be deduced. These are then related to the interaction of the solar wind with the magnetosphere and the resulting energy transfer that occurs. A phased-array bistatic VHF Doppler radar system (SAPPHIRE SOUTH) is also operated from Saskatoon (Sofko, Koehler, Koustov, Hussey) to monitor scattering from E-region plasma irregularities, and thereby to deduce the associated electric fields and currents during magnetically disturbed conditions, particularly magnetic substorms.

The second component is the medium frequency (MF) radar effort, led by A. Manson. It provides information on middle atmosphere dynamics that is important for studying the transfer of energy and momentum in the atmosphere. The information from this radar[5] has been used as a major component of the validation of the WINDII (Canada) and HRDI (U.S.) data sets. It forms an important component of international research on atmospheric dynamics. This is organized under regional and international umbrellas: STEP (Solar Terrestrial Energy programme 1990-97) of SCOSTEP and CEDAR (Coupling, Energetics and Dynamics of Atmospheric Regions) of the U.S. NSF. Manson and Shepherd (York University) have leadership roles in post-STEP programmes using WINDII, Odin and Canadian groundbased systems.

The third major component is associated with Odin/OSIRIS (PI E. Llewellyn), which is an optical spectrograph–infrared imager that will fly on the Swedish Odin satellite—a joint aeronomy-astronomy mission that includes Canada, France and Finland. The space and atmospheric research objectives are directed toward an improved understanding of atmospheric ozone and those processes that control it, particularly at high latitudes. The special features of this small spacecraft are its three-axis stabilization, the sub-mm radiometer and the tomographic capability of the infrared imager. This last is an area in which Canada is providing world leadership. There is also a major ground observing component associated with the Odin/OSIRIS instrument. Other work is associated with the Eureka Observatory; this was established by McEwen during the Centers of Excellence program. One topic that should be mentioned here is the recent development of a truly interdisciplinary approach to space and atmospheric research. Following the Canadian Space Agency (CSA) announcement of a flight opportunity for small payloads, the university put together a multidisciplinary team (Engineering Physics, Electrical Engineering, Mechanical Engineering, Mathematics, and Management) with an industrial partnership (Sci-Tec), and including graduate students, to respond to this opportunity. At the time of writing this work is in progress and will be submitted with every hope of success.

University of Calgary. The University of Calgary has played a leading role in developing auroral imaging from space. Large scale auroral dynamics have been studied using the Canadian uv imagers on the Swedish Viking satellite (launch 1986, PI J.S. Murphree) and more recently the Russian Interball-2 satellite (launch August 29, 1996, PI L. Cogger). Small scale auroral dynamics were investigated by means of the uv imager on the Swedish Freja satellite (launch 1992, PI J.S. Murphree). The group is participating in NASA's IMAGE program by invitation. Auroral and magnetospheric physics have been revolutionized by means of global imaging.

Complementary imaging from the ground has developed in parallel with imaging from space. The group is responsible for the All Sky Imager component of CSA's CANOPUS program. A portable high resolution imager has been used to study small-scale auroral phenomena.

Mesospheric and thermospheric dynamics are studied using a field station equipped with a Fabry-Perot interferometer, a scanning photometer and a spectrometer. The group also participates in the WINDII project on the UARS satellite.

[5]The radar system was significantly upgraded with funds from the Centers of Excellence program.

With the transfer of space plasma physics from NRC to Calgary in 1995, the group has expanded its capability in charged particle detection. The Suprathermal Mass Spectrometer (SMS) is currently in its eighth year of operation on the Japanese EXOS-D satellite (PI A. Yau). Data from the Cold Plasma Analyzer (CPA) that was part of the Swedish Feja satellite mission is being processed at Calgary (PI D. Knudsen). This instrument has unique two-dimensional energy vs. time-of-arrival imaging capability and unprecedented spatial resolution. Two thermal ion detectors were flown on the Oedipus-C sounding rocket in 1995; the processing and analysis is being undertaken at Calgary (PI D. Knudsen).

In planetary science, Canada is providing a thermal plasma analyzer (TPA) for the Japanese Mars mission (launch 1998). The instrument is being built by ComDev with calibration and characterization at Calgary (PI A. Yau, Co-PI G. Garbe).

The Integrated Space Science Facility at the University of Calgary consists of a combination of expertise and specialized equipment for the design, evaluation and operation of satellite instruments. The design capability includes electro-optical detectors, optical instrumentation, and space plasma instruments. Two major components of the facility are the Vacuum UV Calibration Facility and the Particle Calibration System. These systems are supported by both the CSA (contracts) and NSERC (Major Facilities Access Grant), and have resulted in collaboration with Canadian industry in space-related projects.

University of Alberta. The research activity at the University of Alberta concentrates on the interaction between the Earth's ionosphere and the regions of the magnetosphere which supply the energy responsible for auroras and for the large scale electric current systems which permeate the magnetosphere-ionosphere system. One facet of the research centers on the analysis of ground-based data acquired by the Canadian Space Agency's CANOPUS array (PI G. Rostoker). The understanding gained from the ground-based data, complemented with information obtained with collaborators involved in international satellite experiments, provides guidance for the development of sophisticated computer codes that model the development of auroral arcs and the physics of magnetosphere-ionosphere coupling (PI J.C. Samson). High performance computers are required to run these codes effectively. This research, together with studies of SuperDARN auroral radar data, helps to achieve the goal of forecasting "space weather", a major theme in the space research activity sponsored by the Canadian Space Agency.

Memorial University. The work here, under the direction of Summers, is involved in theoretical studies of the space environment.

6.1.1 Relationship with High Technology Industry

It is clearly apparent from the foregoing comments that the major efforts in atmospheric and space physics are indeed collaborative. These efforts have benefited from the relationship with the CSA as the mandate of that government department forces a marriage of the researchers with industry. The collaborative efforts and successes probably began with the development of the Black Brant rocket program and the Alouette satellite almost forty years ago. This was quickly followed by the establishment of SED Systems, a direct spin-off from the space research effort at the University of Saskatchewan in Saskatoon, and the subsequent development of splinter companies within the province. It is safe to say that much of the initial *in situ* space and atmospheric research was initiated from Saskatoon as the University had made a significant investment in the discipline. Indeed by far the majority of Canadian space and atmospheric researchers have some connection with the Institute of Space and Atmospheric Studies at the University of Saskatchewan. However, this research investment also allowed the companies to prosper so that they could move into export markets. Indeed one company, Sci-Tec, has been so successful that it is now almost exclusively in the export sector.

Another "success story" is the company Resonance discussed in Sect. 10.2 (p. 72).

The CSA space research connection has also provided Canadian industry with an opportunity to be world's leaders in space instrumentation. The WINDII instrument was built by CAL in Ottawa following many of the WAMDII design principles developed by SED Systems; the VIKING imager was also built at CAL; the Cold Plasma Analyzer and the MOPITT instruments were constructed at ComDev; for the Thermal Plasma Analyzer a number of small companies were also associated with ComDev; and for the Odin/OSIRIS imager the industrial collaboration has been with Routes Inc. In each case the optical manufacturing abilities for these space instruments have been provided by the Lumonics Optics Group, formerly InterOptics. The involvement of ISTS has also produced a number of successes with Optech perhaps being the most notable.

6.2 Overview of Current Research in Atmospheric and Space Physics

The current Canadian research areas in atmospheric and space physics can be divided into three main topics. In each case these current research areas have achieved notable successes, but many researchers feel that they are under capitalized in both financial and personnel terms.

1. Space Plasmas including auroral studies (Cogger, Garbe, Hamza, Koustov, Knudsen, Laframboise, McEwen, Murphree, Rostoker, Samson, Sofko, St.-Maurice, Yau). This topic is studied using ground arrays of instruments (e.g. CANOPUS, SuperDARN, SAPPHIRE), satellite borne remote sensing instrumentation (e.g. AKEBONO, VIKING, FREJA, INTERBALL Aurora), by *in situ* sampling (TPA on FREJA) as well as through computer modelling and simulation. The measurements, which utilize our natural geographic advantage that the north magnetic pole lies in the Canadian Arctic, and modelling must deal with spatial scales ranging from meters to hundreds of thousands of kilometers and time scales from fractions of a second to many tens of minutes. The object of these studies is to provide a true understanding of the non-linear plasma processes in the geospace environment.
2. Atmospheric dynamics (Manson, T. Shepherd, G. Shepherd, Hocking, Lowe, Sica). This topic involves the use of radars (MF, VHF) and Lidars, optical imagers (WINDII, Eureka Observatory), optical interferometers and modelling (MAM) to provide information on the dynamical state of the atmosphere. The objective is to understand the role of energy and momentum transfer and the coupling of the various atmospheric regions. This work includes the development of novel new instrumentation (e.g. space borne wide angle Michelson interferometers) and the identification and interpretation of geophysical signatures that represent these dynamical transfers (e.g. gravity waves and planetary waves) Canada's regional network is a major contributor to international/global programmes (e.g. CEDAR, STEP), as are Canadian scientists in the development of new programmes (e.g. SCOSTEP; Planetary Scale Mesopause O bserving System, 1997- 2002). The linkage of dynamics and composition/chemistry/aeronomy is now being pursued vigorously bringing into collaboration all atmospheric scientists.
3. Atmospheric and space composition, including remote sensing (Nicholls, McDade, Llewellyn, Carswell, Cogger, Evans, G. Shepherd, Lowe). The original research studies associated with the study of the aurora and airglow were aimed at understanding those processes responsible for the observed auroral forms. However, as knowledge has improved, the idea has emerged of solving the inverse problem in which the composition and state of the atmosphere are determined from the auroral and airglow observations. This work has had some spectacular successes in different

planetary atmospheres, much of it due to the planetary fly-bys, although there has been a major contribution from WINDII and the outstanding work of the Calgary group with the auroral imager. Recently a new approach using active laser sounding (lidars) has developed and is already being exploited for the measurement of ozone as well as for upper atmospheric winds.

However, the tentacles of atmospheric and space physics are much longer than simply these three main topics, they reach into the domain of:

- Image processing
- Modelling, data assimilation and large scale computing
- Laser physics
- Spectroscopy and atomic and molecular processes
- Photonics
- Space borne and ground based instrumentation.

6.3 Opportunities and developments in the Future

All respondents see many opportunities for the future development of their research programs. Essentially, these opportunities can be described as using the present and future short-term findings to develop new methods for remote sensing, the objective here being to provide important forecast information, e.g. space weather and upper atmosphere dynamics, as well as to monitor the atmospheric composition. As the atmosphere and geospace environment is a global one the remote sensing measurements will be global or at least over a wide regional area. Thus there is an expectation that observatories will be located throughout northern Canada and that there will be complementary satellite measurements. This suggests that geospace research will in fact be directed toward activities that will be of concern to Canada.

The development of observatory equipment for operation in remote locations implies that the equipment will in many instances be unattended. This will necessitate the development of environmentally robust instruments with an obvious potential spin-off into unserviced consumer equipment. The global coverage will be provided through new satellite instrumentation, both active and passive, that will be developed through a partnership between university and industry. Successful examples of this partnership are the space-borne imagers WINDII and Odin/OSIRIS; the former is already in orbit and the latter is due for launch in March 1998. Space-borne imagery and its exploitation is an area in which Canada excels; we have developed wide-angle Michelson Interferometers (Shepherd, York University, WINDII/UARS PI), spectral imagery (Kendall, CSA, OGLOW/Shuttle PI), vacuum ultra-violet TDI spectral cameras (Anger and Murphree, University of Calgary, VIKING PI's), and tomographic spectral imagery (Llewellyn, University of Saskatchewan, Odin/OSIRIS PI). It is particularly noteworthy that the VIKING imager has been followed by a series of others that are flying, or have flown, with great success (e.g. FREJA, INTERBALL).

Ground based remote sensing, exemplified in the modern era by the CANOPUS instrument array, plays a powerful role in enabling optimal interpretation of space-based measurements. It also provides valuable guidance for computational modelling of the geospace environment. Over the past two years, the CANOPUS data have been used extensively in studies organized under the International Solar-Terrestrial Physics (ISTP) program. This gives Canadian scientists access to the vast data base presently being acquired by an impressive fleet of spacecraft and other ground based instrumentation such as SuperDARN.

In the case of both the ground-based and satellite instrumentation, there will be large volumes of data generated and it will be necessary to develop high speed communication and analysis links.

One important objective of these geospace studies is to incorporate these data into atmospheric models and models for magnetosphere-ionosphere coupling, both of which describe an essentially nonlinear environment. In this way it will be possible to make the transition from the qualitative description of the environment to a state where algorithms for long- and-short term forecasting can be developed; thus the anthropogenic and solar influences can be estimated and decoupled from one another. Future research will involve the development of global circulation models (GCM's) which will describe both the circulation of neutral gases in the middle and lower atmosphere and plasma in the magnetized environment of Earth's geospace. In fact, computer modelling of atmospheric and magnetospheric processes is one of the important growth areas in the space and atmospheric sciences. It can be expected that in the foreseeable future, advances in computer power and modelling will make many of the nonlinear aspects of the ionized and neutral gases surrounding our planet understandable.

This broad range of research activities provides a superb environment for the training of highly qualified personnel. Students become involved in the development and operation of sophisticated instrumentation, analysis of large data bases using modern analytical techniques, and the development of complex compute codes for modelling space and atmospheric processes. These same skills can be deployed over a wide range of disciplines. Since the type of research carried out is, of necessity, interdisciplinary, the breadth of experience enhances the value of graduate researchers to Canadian industry.

7 Overview of Gravity Research

Canada has had a long and distinguished history of research in gravity and general relativity. Gravity is one of the key areas of physics and one of the foremost areas of intense current research in the world. Not only does it present the fundamental unsolved problem in modern theoretical physics, but also it is eclectic in its links to other areas of modern research.

The following sections first outline the background history in Canada and the current status internationally in order to put the discussion of gravity research in Canada into its proper context.

7.1 Background History

Einstein's theory of General Relativity as a replacement for Newton's theory of gravity first appeared in 1915. It then largely languished as a physical theory for the next 40 years. After a brief flurry of experimental results, including the deflection of light by the sun and the explanation of the precession of the perihelion of Mercury, the theory became primarily an arena for mathematical investigation. The differences between Einstein and Newtonian gravity were beyond the technological abilities at the time to measure, but it did introduce new mathematical and physical concepts for a theory of nature. It was in trying to understand the mathematical framework of the theory that research was concentrated for those years.

In this endeavour, Canada played a distinguished role. Already in the 1920's, J. L. Synge, the great Irish mathematical physicist and general relativist, came to Toronto as an assistant professor, and subsequently as head of Applied Mathematics until he returned to Ireland in the 1940's. In addition to his outstanding research and his founding of the world's top prize in Mathematics, the Field's Medal, he was also the teacher and collaborator of one of the pioneer relativists in the U.S., A. Schild. After his return to Ireland to the Institute for Advanced Study in Dublin, he was responsible for helping to train W. Israel, who subsequently came to Canada.

In the 1940's and 50's, Max Wyman pioneered the study of relativity in Edmonton at the University of Alberta, making his name with a series of exact solutions of both general relativity and of Einstein's unified theory. His presence at Alberta became one of the key attractions for W. Israel to come from Dublin to the mathematics department at Edmonton.

Also in the late 30's L. Infeld, one of Einstein's chief collaborators, came to the University of Toronto. He left in 1950 for Poland because of the growing tide of McCarthyism in Canada.

In the 1950's to the early 70's, H. Rund, a differential geometer, and later his student D. Lovelock, dominated the field at the University of Waterloo. Lovelock's study of the complete set of invariant actions in arbitrary dimensions leading to second order metric theories of gravity, has become of crucial importance in the study of string theories today. Although they both eventually left for the United States, they left behind an important group which still exists in the Applied Mathematics Department. Of note was the work of R. McLenaghan with N. Kamran on the relation of the separability of the wave equations in the Kerr (rotating black hole) metric to the existence of a Killing tensor.

The late 1950's brought R. Skinner as a pioneer relativist to the University of Saskatchewan. In addition to his research in general relativity, his text book on special relativity is still one of the best.

In Toronto, in the late 60's and early 70's, R. Roeder began studying the physical consequences of general relativity. With his student, C. Dyer, he founded the study of gravitational lensing as a tool for determining the matter distribution in the universe, a technique which was to come to fruition with the work of Kaiser, also at Toronto, in the 90's (to be mentioned later). Although he moved to Arizona in the late 70's because of the Canadian funding situation, he left in Canada three of his students, K. Lake (at Queens), C. Dyer (at Toronto), and S. Pinnault (Laval), now an astronomer.

Also at Toronto, John Moffat began his research into an alternative theory of gravity. The theory itself has led to a deeper understanding of general relativity, and in the process he trained a number of excellent Canadian researchers, such as R. Mann, G. Kunstatter, and D. Boal (now in Chemistry).

At the University of Alberta, Werner Israel, who has dominated the field of mathematical relativity in Canada from the mid 60's to the present, carried out his pioneering work on black holes in the late 60's. It was his work which formed the first step toward the "No Hair" theorems for black holes, a set of statements that all black holes could be completely characterized by their mass, charge and angular momentum alone. In addition, with his summer school in 1972 on Relativity, Cosmology and Astrophysics, he made Canada a focal point for research in the field.

Throughout the 60's there was a constant stream of hirings across the country in mathematical relativity, placing at least one person at the major universities across the country. Unfortunately, by not building groups, these individuals tended to be isolated and not to have as big an impact on the world scene as they could have had.

The 1970's brought W. Unruh first to McMaster University, and then to the University of British Columbia. His work on quantum limits to gravity wave detection, on scattering of fields by black holes, on the quantum radiation from black holes which had been discovered by Hawking, and on the thermal nature of the vacuum as seen by an accelerated observer, had a significant impact internationally.

The field was and is thus dominated in Canada, as in most of the world, by theorists and mathematicians. Canada had one major foray into the field of experimental relativity with the gravity wave detection experiment mounted by Papini and Tward at the University of Regina. Although strongly supported by NSERC and the University for a time, it ultimately foundered on the immense technological difficulties presented by the experiment.

In the application of Einstein's theory to the origin of the universe itself, namely the field of Cosmology, Canada has long enjoyed a strong astronomical observational contingent. For the purpose of this review, we will not discuss this observational component, but concentrate on the theoretical side. Until the late 80's, theoretical physical cosmology had been virtually nonexistent. Except for the work of Roeder's group, and scattered efforts by a few individuals elsewhere, there had been little impact by Canadian theorists on the field. This changed radically with the formation of CITA (Canadian Institute for Theoretical Astrophysics) at Toronto in the late 80's. Through the superb support of NSERC, the University of Toronto, and the new Canadian Institute for Advanced Research (CIAR), Canada suddenly became a world center for cosmology and astrophysical gravity theory, with the hiring of Scott Tremaine as Director of CITA and of Dick Bond and Nick Kaiser as faculty members.

7.2 Current Status of Gravity Research Internationally

This section outlines the current status of gravity research on an international scale. The review will of necessity be very brief and incomplete. It is intended give the flavour of the subject today before discussing the Canadian context.

As indicated in the preceding section, Canada has had a long history of research in gravity and general relativity. However it was primarily carried out by isolated researchers scattered across the country who were primarily interested in elucidating the rich mathematics of the theory. Canada was not unusual in this, as this also described the state of research in the world community. It was only in the early 70's, especially with the impact of the Wheeler school in the U.S., of Sciama in the UK, and of Zeldovich in the USSR that the field suddenly took off as a study yielding profound insights into the physical world. Throughout the 30's and 40's, it had been realised that the theory could make predictions about the origin of the universe—predictions which reached their culmination with the discovery of the cosmic microwave background radiation (CMBR) in the 60's. However, the use of general relativity to describe the expansion of the universe did not delve deeply enough to reveal unexpected features of the theory.

This was altered by the realisation that the theory predicted objects called black holes, with all of the counterintuitive features that these objects possessed. Furthermore, these black holes could have observable consequences for astronomy, and they were soon invoked to explain the highest energy astrophysical phenomena, namely quasars. Furthermore, with the work of Penrose and Hawking in the UK and Wheeler and his students in the U.S., it quickly became clear that this new aspect of the theory contained a rich array of physical predictions, so much so that this mine is still far from exhausted. Thus, the elucidation of the physical consequences of black holes and other such objects predicted by the theory still forms one of the chief research areas worldwide.

In the mid 70's came another shock. In trying to combine quantum mechanics with black holes, Hawking discovered that such objects should not be stable, but rather should slowly dissipate their mass and energy as radiation through a still ill-understood quantum process. Furthermore, such quantum effects would also be expected to play a dominant role at the formation of the universe. These studies highlighted more than ever the chief embarrassment of theoretical physics—that there exists no theory which combines the quantum picture of matter with gravity. This problem is bringing together gravity theorists and particle theorists in an interdisciplinary effort to unify the two fields. The result will undoubtedly be the greatest achievement of physics, yielding profound new insights into the nature of the universe.

Particle physics and gravity physics must also be combined to explore the gravitational consequences of matter under the ultrahigh temperatures and densities present in the early universe. It was people like Guth, Linde, Steinhardt and others who realised that these combined effects could dominate the early evolution of the universe, giving us the possibility of explaining its form and structure. Elucidating the consequences of these ideas is one of the field's most active areas of research.

In addition to the theoretical approaches, modern technology has also allowed us to begin testing the theory through observations and experiment. The classic solar system tests have become ever more accurate in the past 20 years. In addition, a number of new areas have opened up. One of the most difficult has been that of gravity wave detection. Terrestrial detection demands the measurement of changes in length of one part in 10^{-21}. Inspired by the now discredited detections of Weber (U.S.) in the mid 70's, it was realised that gravity waves from realistic astrophysical sources were at the technological edge of detectability. This work has been further inspired by the detection of the energy loss by gravity waves of a binary pulsar by Hulse and Taylor (U.S., Nobel Prize 1994). Furthermore, other experiments to test the theory have also been developed, such as the Stanford gyroscope experiment, which, while it lies at the edge of our ability, gives hope that more and more of the theory will be underpinned by experiment. The growing impact of General Relativity is marked by the way in which it is transforming itself from an esoteric irrelevance to a common tool of observation. In addition to black holes having been accepted as a constituent of the universe, gravitational lensing has become a powerful tool with which to discover the matter in the universe, whether in the largest scale as in the work of Kaiser described below, or in the MACHO project looking for small dark constituents of our galaxy.

In all of this the mathematical structure of the theory continues to reveal surprises as new methods of attack are developed. One of the most unusual is the revelation that numerical techniques can disclose totally unexpected features, as in the work of Choptuik described below. Another example is in chaos theory, where General Relativity is casting new light on ideas which originated in other fields of science.

More normal computational techniques are also increasing in their crucial contributions to the field. This is true in classical Newtonian gravity as in general relativity. One of the Grand Challenge projects funded by the NSF in the U.S. is in the numerical solution of black hole collisions. This effort clearly reveals that the depth of our understanding of general relativity is still too shallow, and extensions both numeric and analytic techniques are essential to further progress.

The ideas, insights and techniques of general relativity extend far beyond the confines of the field. A small example is provided by the recent flurry of interest in the world in quantum computing. This is the idea of using the quantum properties of matter in an essential way in building computers which are far more powerful than any classical "Turing machine" in being able to solve certain problems exponentially more rapidly. One of the key contributors to this field has been R. Laflamme, a former Laval undergraduate now at Los Alamos whose doctoral training at UBC was in quantum gravity. It is more true today than ever that theoretical physics is a single entity, with individuals applying a common pool of techniques and problem-solving abilities to their particular speciality. The universality of physics is further discussed in Sect. 8 (p. 53).

7.3 Principal Centres of Activity in Canada

Table 2 lists the researchers in Canada who have an interest in general relativity. In some cases this interest forms a part of a broader interest in other areas of physics, mathematics and astronomy. The list includes all those supported by GSC's 17 and 29, along with those supported by Mathematics (M), and Computation and Information Science (C). Tables 35 and 37 on pp. 138 and 150 respectively give additional information for those supported by GSC's 17 and 29.

Among the various centres of activity in Canada, one of the most significant is the Canadian Institute for Theoretical Astrophysics (CITA) at the University of Toronto. The group there, now directed by J. R. Bond and including N. Kaiser and S. Tremaine, have made this one of the top institutions in the world in the study of gravity in connection with astrophysical problems. From Newtonian gravity and the study of black holes in the center of galaxies, to the impact of gravity on the very early universe and the formation of structure in the universe, to the use of the general relativistic lensing of light by matter as a measuring tool for the distribution of matter in the universe, their research has had a significant international impact on the field. It forms a prime example of the way in which Canada, with cooperation among the premier research agencies in Canada (NSERC, CIAR[6], and the University), can dominate a field of science in the world. It is also an example of the fragility of such efforts, and the difficulties which Canadian physics faces in being a powerhouse in any area in that two of their top people will leave for positions in the United States. Although such changes are inevitable for the top researchers in the country, the competition (which we expect to increase in the next five years) will be difficult for Canada, especially in light of the substantially higher salaries offered in the top U.S. universities.

Another area of strength has been built up at the University of Alberta over the past five years. Starting with Canada's premier mathematical general relativist, W. Israel, they have built up (again through the cooperation of the University and the CIAR) a very strong internationally recognized group in classical and quantum gravity with the arrival of D. Page from the U.S. and V. Frolov from the USSR.

[6]The Canadian Institute for Advanced Research (CIAR) is a private institution funded by donations from industry, philanthropic organizations, and various levels of government. The gravity program has recently been renewed for its third five year term.

Table 2: Canadian researchers in general relativity and gravity.

Name	University	GSC	Name	University	GSC
Mathematical Relativity			**Quantum Gravity**		
Coleman, A.	Regina	M	Frolov, V.	Alberta	17
Coley, A.	Dalhousie	17	Page, D.	Alberta	17
Collins, B.	Waterloo	M	Prugovecki, E.	Toronto	M
Cooperstock, F.	Victoria	17	Unruh, W.	UBC	17
Couch, W.	Calgary	M			
Das, A.	Simon Fraser	C	**Cosmology and Astrophysics**		
Dyer, K.	Toronto	17			
Glass, E.	Windsor	17	Bond, J.R.	Toronto	17
Gravel, P.	RMC		Carlberg, R.	Toronto	17
Harriot, P.	Mt. St. Vincent		Clutton-Brock, M.	Brandon	
Hewitt, C.	Ryerson	17	Couchman, H.	Western	17
Israel, W.	Alberta	17	Duncan, M.	Queens	17
Kunzle, H.	Alberta	17	Halpern, M.	UBC	17
Lake, K.	Queens	17	Henriksen, R.	Queens	17
Ludwig, G.	Alberta	M	Hewitt, C.	Waterloo	17
McLenaghan, R.	Waterloo	17	Kaiser, N.	Toronto	17
Osborn, T.	Manitoba	29	Scott, D.	UBC	17
Papini, G.	Regina	29	Tremaine, S.	Toronto	17
Pechlaner, E.	Simon Fraser		Wesson, P.	Waterloo	17
Poisson, E.	Guelph	17	Williams, J.	Brandon	17
Rastall, P.	UBC				
Schleich, K.	UBC	17	**Particle Physics**		
Sniatycki, J.	Calgary	19			
Soler, F.	Moncton	17	Gegenberg, J.	U.N.B.	17
Torrence, R.	Calgary	M	Kunstatter, G.	Winnipeg	19
Tupper, B.	New Brunswick	M	McKeon, G.	Western	19
Wainright, J.	Waterloo	17	Mann, R.	Waterloo	17
Witt, D.	UBC		Meyers, R.	McGill	19
			Moffat, J.	Toronto	17
Numerical Relativity			Vincent, D.	Winnipeg	
			Widrow, L.	Queens	17
Hobill, D.	Calgary	17			
Mann, P.	Western	17			
Poisson, E.	Guelph	17			
Schleich, K.	UBC	17			

At the University of British Columbia, a diverse group, with strength in observational and theoretical cosmology, and in classical and quantum gravity has again arisen in the past ten years through the recognition by the university and the assistance of the CIAR that this is one of the most exciting fields of physics today.

In addition, we would point to other groups, such as the group at Waterloo/Guelph in mathematical relativity and the links of relativity to particle physics, or to Queens University where again there is strength in astrophysical gravity and in the links between particle physics and the early universe.

7.3.1 Role of the CIAR and CITA

The impact made by the Canadian Institute for Advanced Research (CIAR) and by the Canadian Institute for Theoretical Astrophysics (CITA) on the field in Canada have been so significant that it is worthwhile detailing these institutions.

The CIAR was founded in the mid 80's to try to establish a front line research establishment in Canada. Because the founders felt that the university structures suffered from too large a divergence of interests to enable any one of them become world centers of research, and because there was simply no money available to establish a single institutional center, it was decided to invent a new structure. In this, the CIAR would fund researchers located at the various universities across the country. These funds were to allow the researchers to interact with each other on a continual basis, and provide them with the relief from other university duties to allow them to concentrate on research.

The program in Cosmology (now Cosmology and Gravity) was the second program to be established by the CIAR with Unruh as its founding director (now with S. Tremaine as director). Within five years, this program had managed to bring to Canada four exceptional researchers (Bond, Kaiser, Page and Frolov), who helped to convert Canada from a somewhat peripheral player in the field to one of the central players in the world in the area of cosmology and gravity. In addition the funds also allowed interaction between the Canadians and selected researchers from around the world.

In each case, the recruitment came from the universities involved, and their participation was critical. However, in each case those attempts would have been doomed had it not been for the lure the CIAR provided of working with a group of world renowned researchers from across Canada (and the world).

At the same time as the CIAR program formed, the Canadian Astronomical Society decided to catalyse the formation of a Center for Theoretical Astrophysics, since theory had long been a weakness in Canadian astronomy. Thus, they instituted the Canadian Institute for Theoretical Astrophysics (CITA), located at the University of Toronto. The effort to establish CITA was led by R. Henriksen and P. Martin (Toronto), who have also continued to guide its growth. They obtained S. Tremaine from the U.S. as their first director, and at the same time hire Bond from Stanford, and slightly later, N. Kaiser from the UK. While the formation of both groups was independent, it was only because of the research environment provided by CIAR that CITA was able to become one of the world centres for theoretical astrophysics and in particular, for cosmology, in a very short time.

7.4 Outstanding Canadian contributions

There are three outstanding Canadian contributions to the field which which we wish to highlight. They illustrate not only the high international standard that has been achieved in Canada, but also the diversity of people and areas for which that capability exists.

1. Gravitational Lensing. One of the outstanding problems in the study of the large scale structure in the universe is the determination of the distribution of matter. While some of the matter makes itself known by the light it emits (eg stars, interstellar or intergalactic gases, etc), the proportion of the total which is thus visible, and the distribution of the total mass, light and dark, are crucial open questions. Although Roeder and Dyer realised the importance of gravitational lensing as a potential tool for examining the matter in the universe, it took the invention of the CCD camera to make this tool a reality. Following J.A. Tyson's (U.S.) demonstration of the existence of the gravitational lensing of the vast population of very faint distant galaxies by closer clusters of galaxies, Nick Kaiser of CITA (Toronto) realised that this could be turned into a practical tool for determining the distribution of all matter in the universe, whether visible or not. Since all matter has a gravitational field, and since all matter thus causes the lensing of light from those faint distant galaxies, by measuring this lensing, one could directly measure where the matter in the universe lies, and how much of it there is. With his student, N. Squires, Kaiser developed the technique of using the statistically measurable distortions of the shape of those distant galaxies to measure the total distribution of matter in the nearby clusters of galaxies. This technique represents the first tool able to get a direct handle of one of the most crucial parameters of the early universe.

2. Critical Exponents and Black Holes. M. Choptuik was a student of Unruh's at UBC. After a U.S. postdoctoral position, he spent the next four years at CITA in Toronto. It was there that he made one of the most unexpected discoveries about the nature of Einstein's theory of gravity, and in the most unexpected way. Numerical studies are usually considered a means for obtaining more accurate answers to questions about phenomena which are, in general outline, well understood. Rarely in any field do numerical studies reveal fundamentally new phenomena, unexpected by other means. However, he demonstrated that numerical techniques can be used to discover and understand genuinely new and unexpected phenomena.

He showed that black hole formation can be viewed as a type of phase transition (usually associated with condensed matter systems), in which the critical point, the point where one just has enough energy to form an infinitesimally small black hole, is dominated by complex critical exponents. Just near this critical point, the matter forming the black hole goes into a self similar oscillation in which it alternately collapses almost to a black hole, and then re-expands with most of the matter escaping, but the remainder repeating the same cycle on a much shorter time scale. Such complex, oscillatory behaviour is only now beginning to be studied in condensed matter systems (where such critical behaviour has been studied for at least 20 years). This research is probably one of the nicest pieces of work to come out of theoretical general relativity in the past 20 years, and it illustrates the potential for other surprises. It also illustrates how numerical studies can become a laboratory for discoveries about the theory in the same way as laboratories make discoveries about nature.

3. Structure of Black Hole Interiors. Werner Israel, and his students (especially E. Poisson) began to investigate the interior structure of black holes in the early 90's. While the expectation was that all singularities within a black hole had roughly the same, "$r = 0$" form (ie that the angular size of the singularity essentially went to zero) they found that in the case of charged or rotating black holes the singularity structure generically was very different. These spacetimes, in the presence of matter, developed an internal singularity in which the singular surface formed at finite r. The curvature and energy density diverged long before that matter had been crushed to zero.

Israel has called this "mass inflation" because, to a freely falling observer, the mass represented in the curvature of the spacetime increases far faster than they would have expected on the basis of the Schwarzschild solution. The exact delineation of the singularity and of the formation of these singularities has become an international effort with significant input from people using numerical techniques.

7.5 Recent Research Accomplishments

This section briefly reviews some of the research being carried out in Canada. The review will not be exhaustive, and will neither describe the full scope of the research in the country nor even the full scope of the interests of the people mentioned. It is intended to illustrate the breadth of the recent research and the way in which Canadian research links into international efforts in this area. The organization is by topic, rather than by institution where the research is done. People mentioned without an affiliation are the current Canadian researchers listed in Table 2. The work described is current or relatively recent research. Historical contributions are discussed in Sect. 7.1 (p. 41).

1. Black Holes. Black holes remain one of the key testing grounds for our understanding of general relativity. From the possibility of their existence itself to the fact that they can evaporate due to quantum processes, and so on, they have consistently dealt us surprises. Canadian researchers have continually been highly visible internationally in this area ever since the pioneering work by Israel in the early 70's. The work by Israel and his students on the interior of black holes is already discussed in Sect. 7.4 (p. 47). Another noteworthy result in this classical theory of black holes was by Kunzle and Masood-ul-Alam who, together with others, showed numerically that black holes could exist with Yang Mills "hair"; i.e., having a nonzero Yang Mills field exist in a time-independent manner outside a black hole. These results extend the types of black holes that the theory allows to exist. The situation in the case of quantum black holes is richer. The evaporation process discovered by Hawking for black holes is still poorly understood. Not only is the origin of the thermal radiation still mysterious, but also is the entropy associated with black holes. No statistical mechanical origin for this entropy has ever been discovered. In this area, we would like to single out a number of results.

Unruh already in the early 80's had discovered that black holes could be mimicked in some of their quantum thermal properties by hypersonic fluid flows. Work in this model done recently has given support to the low energy nature of the thermal radiation (which in the conventional approach is caused by the ultra high energy behaviour of the fields near the black hole horizon). This ties in with work by Frolov, who has shown that the free energy of a black hole, regarded as a thermodynamic object, differs from most other systems in that the temperature and the energy are not independent. This changes the high energy behaviour of the theory so as to remove the singularity from the normal calculations of the entropy and free energy, again lending support to the view that the evaporation process and the entropy are low energy processes. These results may also tie in with results by Strominger (U.S.) from string theory in which the entropy of black holes can be calculated, although the meaning of these calculations is still obscure.

A second area in black hole physics is the result in the classical theory of general relativity by Witt and Schleich (in coauthorship with Friedman (U.S.) on topological cosmic censorship. Not only do singularities hide themselves behind the skirts of horizons (surfaces out of which even light cannot escape to infinity) but so do any localised topological peculiarities.

Third, black holes have also formed the basis of attempts to understand quantum gravity. Following work by Kuchar (U.S.) and others, Braham (PDF at UBC and UNB), Gegenberg, and

Kunstatter have used black holes as models systems for quantization. Despite their apparently trivial nature (one conserved quantity and no dynamics) the quantization has thrown new light on the nature of time in a quantum theory of gravity.

A fourth area in which black holes have formed the basis for significant work has been numerical. In addition to the work of Choptuik mentioned above, one of the U.S. Grand Challenge projects has been in the numerical relativity. Although not members of this project, work by Hobill, P Mann and a student of Unruh, J. Thornburg have contributed to the effort. For example Thornburg and Unruh suggested a technique of numerical horizon avoidance which has become of key importance in that Grand Challenge.

Finally, black holes have also become astrophysical objects. How can we discover them? Tremaine is one of the principal investigators in an international collaboration to answer this question. They are showing that black holes exist at the centers of a number (if not most) of galaxies.

2. Cosmology. How do gravity and particle physics theories combine to explain the features of the universe in the large? This is again a very hot topic internationally, especially with the possibility of testing some of the predictions experimentally. Here the work of the people at CITA has been of crucial importance, both the faculty members and the extensive number of postdoctoral fellows which NSERC's support has enabled them to support. In addition to being the world's foremost interpreters of the results of the Cosmic Microwave Background radiation satellite and ground based experiments, Bond and his students (especially Salopek) have been key in their work on predicting the density fluctuations coming from the inflationary paradigm. Other work by postoral fellows at CITA, such as the potential for cosmic strings to explain the structure of the universe (Stebbins), and ways in which the phenomena of particle physics could alter the matter distribution in the universe (Starkman, Kofman, Widrow), have helped to ensure that CITA is one of the foremost centers of cosmology in the world.

In quantum cosmology, the study of how quantum processes could bring about the birth of the universe and affect its current structure, we would single out the work of Page whose research into the nature of quantum gravity both in the early universe and in black holes has had a strong impact internationally.

3. Chaos. Over the past 20 years, chaos theory has had a strong impact on our understanding of physics. Is general relativity also chaotic? This problem has turned out to be far from trivial. Most standard measures of chaos examine the behaviour of the system with respect to time. General relativity has forced people to look for new measures which are independent of the particular coordinate system used. In these investigations, we would particularly single out the work of Wainwright, whose recent book *Dynamical systems in cosmology* (Cambridge University Press, 1997) sets a high standard in this field. In addition, numerical work by Hobill and analytic work by Coley and Dyer have also had their impact in this area.

It is important to realise that numerical relativity and the more classical mathematical relativity are not distinct, as both attempt to solve and to understand the classical equations of general relativity. As such they are complementary. For example, the purported existence of naked singularities shown by Choptuik's work (which has received recent publicity), is closely related to previous work by mathematical relativists like Henriksen and collaborators and Lake and collaborators in their study of naked singularities in homothetic and other spherical solutions of the equations.

4. Particle Physics. In addition to the impact of particle physics on cosmology, probably the area in which particle theory has had its greatest impact on gravity has been in string theory. The hopes are that string theory can describe all of the interactions of matter, including gravity. As mentioned above, the work on black hole entropy in string theory strengthens the hope that this promise will be realised. In this context we would like to single out the work of R. Myers at McGill with B. Campbell at Alberta (whose work concentrates more on the particle physics aspects of string theory). They are essentially the only string theorists in Canada. As discussed in Sect. 11.4 (p. 83), this is one of the current weaknesses.

Also in this area, R. Mann and his students have been using techniques from particle physics to address basic issues in general relativity, such as new tests of the equivalence principle in the nonbaryonic sector of the standard model. As an experimental test of theories of gravity, their search for and setting of an upper bound to the optical activity of gravity, predicted by some theories, was particularly noteworthy. Their work in lower dimensional black hole models has also attracted international attention.

5. Computational Gravity. As mentioned in Sect. 7.4 (p. 46), the numerical solution to Einstein's equations has become one of the most useful tools in the field. The full four dimensional (three space and one time) solution still exceeds the ability of even the most powerful computers, except on problems where low resolution is tolerable. The work of Hobill and Mann gives Canada important potential for future participation in this area.

Even in Newtonian theory, computers have a large impact. One of the areas of Canadian expertise is in the numerical simulation of the solar system. while crude simulations are trivial, the accurate simulation over time spans of millions of years is a problem which taxes the boundaries of our abilities. The vastly divergent time scales (from a month for example for the moon to decades for the outer planets) make challenging the construction of efficient techniques. It is only through such simulations however that one can answer the age old questions about the stability of the solar system. In this area Tremaine and his students are world leaders. Both Tremaine and Duncan had asteroids named after them in 1997 in recognition of their pioneering work.

Another even more challenging area of computational relativity has been to try to make inroads into questions about quantum gravity. As has been discovered in condensed matter systems, because of the vastness of Hilbert space, quantum computations are far more difficult than classical ones. However one can still hope to use computational techniques on simple enough systems to get interesting answers. This is an area where Schleich and Witt are working, developing both the computational and the analytic tools for attacking this question.

The use of computers to take the drudgery out of even analytic calculations is one of their great benefits. Thus the extension of algebraic manipulation languages (e.g. Maple or Mathematica) to general relativity plays a very useful role, and furthermore raises fundamental issues in the representation of algebraic forms on the computer and for presentation to the user. Canada has three people, all of whom have done very useful and innovative work in this area. R. McLenaghan has developed a number of geometry packages for Maple, K. Lake and his students have developed the powerful `GRTensorII` package for Maple and `GRTensorM` for Mathematica, and C. Dyer developed the `muTensor` package for muMath and `Redten` for Reduce. All of these have been very useful tools. The first is a standard package in the commercial full version of Maple, while the latter two have been released at no charge.

6. Experimental Gravity. Since the abandonment of the Regina gravity wave experiment (see Sect. 7.1, p. 42), Canada has no experimental work in gravity *per se*. Rather, Canadian research has an impact on the theory which backs the experiments carried out in the rest of the world. Because of the huge expense of such experiments, this is probably a far more efficient use of our money. It is far easier to create a group with a world impact in theory than it is in experiment. One of the people particularly working in this area is E. Poisson (Guelph). His work and others show that the approximation techniques we now have for calculating the detailed form of emitted gravity waves are not adequate, even for idealised sources. This work highlights one of the problematic features of general relativity. The theory contains no natural "small parameters" upon which one could base an approximation scheme. Thus, finding accurate predictions is much harder than in most other theories. Furthermore, the demand for accurate calculations is acute because of the terrible signal to noise ratio expected for the first generations of detectors.

The above has simply touched on a number of topics in which Canada has made strong contributions to the fields of gravity and general relativity. This is not an exhaustive survey, and many strong contributions have been omitted. It is intended to give some feeling for both the diversity and the strength of the Canadian research presence in this area.

8 Theory

Perhaps in no other discipline are the links between theory and experiment as close as they are in physics. The progress of physics can be marked by the degree to which an ever-expanding range of phenomena can be brought under a common umbrella of understanding. Theory allows one to view apparently diverse phenomena as different aspects of the same thing. In this regard, theory provides the supreme form of "technology transfer", where ideas and techniques developed for one area can with great rapidity be applied to another completely different area.

As an example, the techniques of many-body perturbation theory originally developed for subatomic physics are now routinely applied to the structure of atoms and condensed matter phenomena. The quantum field theory formalism originally developed to account for the Lamb shift in hydrogen atoms is now widely applied, for example, to quantum optics and low-temperature phenomena in solids. It forms the template upon which other theories of elementary particle interactions are built. Virtually all the laws of physics can be expressed in terms of variational principles that have a close formal similarity. Computational methods based on variational principles cut across all areas of physics, and provide a powerful means of practical computation. Other methods of numerical solution of systems of differential equations, computer modelling and Monte Carlo techniques are immediately transportable from one area of physics to another. A striking example is provided by the equations of motion of a light wave near the event horizon of a black hole, which are formally identical to the classical hydrodynamic equations of sound waves in an accelerating fluid stream (Unruh).

The basic electromagnetic interactions responsible for the range of phenomena covered by General Physics are now well known. However, only the simplest of problems are amenable to exact analytic solution. For the vast majority of cases of experimental and practical interest, approximation methods must be developed along the lines described above. The validity of these approximations must be tested by comparison with experiment. However, once established, the approximation methods are of great utility in extending known results to other unknown cases. The calculation of scattering cross sections, radiative transition rates, and other atomic and molecular properties is an important example. It sometimes happens that a tiny correction to the theoretical analysis of one case can be made the dominant physical effect in another by a suitable adjustment of parameters. The result may be a whole new range of phenomena with important applications in areas such as photonics, plasma physics, or the design of lasers. Despite the best efforts of theorists, complex systems sometimes display collective phenomena which must be first discovered in the laboratory before an adequate theoretical description can be obtained. Of great current interest are the collective phenomena displayed by clouds of atoms undergoing Bose-Einstein condensation in an optical trap. These studies are already yielding unexpected results that are providing fresh challenges to theorists.

In summary, theory, together with many common elements of experimental technique and instrumentation, provide the glue that ties together the diversity of topics covered by General Physics.

8.1 Theoretical Atomic and Molecular Physics

Theoretical atomic and molecular physicists form one of the largest communities of theoreticians in Canada, with 22 researchers supported by GSC-29. The activities can be broadly divided into atomic and molecular structure, and scattering phenomena. Those involved primarily with atomic and molecular structure are S. P. Goldman, T. M. Luke and J. D. Talman at the University of Western Ontario, and W. E. Baylis, G. W. F. Drake, R. D. Kent and M. Schlesinger at the

University of Windsor. Some particularly significant recent accomplishments are:

- the calculation of essentially exact solutions to the nonrelativistic two-electron helium problem and other three-body systems (Drake), thereby allowing high precision comparisons between theory and experiment for higher-order relativistic and quantum electrodynamic effects. A long-range goal of this work is to obtain an improved value for the fine structure constant, and to obtain results of similar accuracy for lithium and heavier atoms. The results for both helium and lithium are the most accurate in the literature, and they are stimulating considerable activity amongst experimentalists world wide to perform measurements of comparable accuracy for comparison.
- the development of techniques which dramatically improve the accuracy of configuration interaction calculations for multi-electron atoms (Goldman). This work has the potential to revolutionize the way calculations of this type are done for molecules as well as for atoms.
- the development of unitary group methods and their computer implementation for the theory of complex atomic spectra (Kent, Schlesinger, Drake). These techniques are being increasingly used in large scale calculations of atomic structure.

Continuing challenges include the development and refinement of variational methods which explicitly incorporate relativistic effects (Talman), and the development of approximation methods for energy levels, transitions and autoionizing resonances in complex ions (Luke).

There are several groups involved with scattering calculations. At York University, the group of R. P. McEachran and A. D. Stauffer is well known for their calculations of electron and positron scattering from atoms, including recent interest in alignment and orientation effects, and the Monte Carlo modelling of x-ray detectors. M. Horbatsch is developing methods to treat excitation and ionization in ion-atom collisions in the low to medium energy range where classical trajectory methods fail. New developments are expected in the area of cooperative phenomena arising from the many-particle aspects of ionization. At Waterloo, M. C. Chidichimo and W. K. Liu are involved in systematic studies of the excitation and ionization of positive ions by electron and proton impact, and in multiphoton excitation processes. This work contributes particularly to the great need for such data in plasma modelling. At Laval, L. J. Dubé explores the validity of various approximation methods to describe fundamental scattering problems such as electron capture into particular final states in proton scattering by hydrogen. Even this simplest of scattering systems continues to defy precise analysis except in the limit of high energies. Similar work is done by T. T. Gien at Memorial University, as well as fundamental work on algebraic close-coupling methods for positron scattering from hydrogen.

8.2 Theoretical Plasma Physics

An accurate theoretical description of plasma processes is a challenging problem involving components of all the topics covered by General Physics from classical fluid dynamics and statistical physics to the detailed calculation of scattering processes and radiative interactions. Plasmas produced by intense laser fields is a topic of particular current interest. Applications to the controlled fusion program are especially important, but there are many other areas, such as plasma processing of surfaces, plasma reactors, lighting sources, and astrophysical applications where a detailed understanding of the formation and evolution of plasmas is essential.

In Canada, the three principal centres for theoretical plasma physics are INRS in Québec, the University of Saskatchewan, and the University of Alberta. All of these centres are associated with tokamak or inertial confinement fusion programs. At INRS, R. Marchand has been very successful in developing finite element methods on unstructured meshes for the computer modelling of tokamak plasmas. This work helps in the extrapolation of present fusion experiments to the next generation of reactor experiments, but the same techniques can be applied to a large class of other computer simulation problems involving complex systems and realistic geometries. Also at INRS (Johnston, Matte), and at Alberta (Capjack and Rozmus), research is progressing to model theoretically the interaction of intense laser beams with hot plasmas. This work is particularly exciting because the available laser intensities are now entering a new regime where the electron oscillations in the plasma they produce become relativistic. The results have important implications for both inertial confinement fusion, and for the possibility of producing a new type of particle accelerator.

At Saskatchewan, A. I. Smolyakov had developed a broad multidisciplinary program to study the behaviour of both naturally occurring plasmas, and those artificially created for laboratory and industrial applications. In conjunction with the STOR-M tokamak, he has been influential in advancing theoretical understanding of self-organized rotating magnetic structures in fusion devices, and devising methods to control their degrading effects. Other aspects of this program contribute to multidisciplinary research into the many applications of low temperature plasmas to areas such as plasma reactors to remove harmful pollutants from industrial exhaust gases, the development of devices for monitoring the ozone layer, and the development of physical models for the ozone dynamics. Many other plasma-based technologies are currently emerging in areas such as sterilization of food, medical products and instruments, gas discharges for lighting and lasers, isotope separation, switching and welding technology, and plasma-based space propulsion systems. We can expect to see rapid advancements of plasma-based technologies into industrial manufacturing over the next five to ten years.

The above examples clearly illustrate the multidisciplinary nature of plasma physics from two points of view. First, a fundamental understanding of plasma physics relies heavily on input from many other branches of physics. Second, the applications range very broadly from atmospheric and space physics to the industrial processing of materials and controlled fusion devices. Many of the theoretical techniques are generally applicable to the study of complex nonlinear systems.

8.3 Fundamental Theory and Mathematical Physics

The theoretical programs discussed thus far are more or less clearly identified with particular experimental programs or applications. There is in addition an important group of theorists working on more fundamental problems concerning field theory and its applications to particle interactions and nonlinear dynamics. A large and important part of this are the theoretical programs in general relativity and gravitation already discussed in Sect. 7.3 (p. 44). Although this work is of a more general nature, it is an essential part of the intellectual viability and dynamics of the field, and it plays an important role in unifying the diverse branches of physics by emphasizing their common elements. The methods of classical and quantum field theory are often applicable to broad classes of problems in otherwise unrelated areas, and much fruitful work has been done by taking advantage of this in all branches of physics. Those involved in various aspects of field theory from GSC-29 are J. A. Tuszynski (Alberta), B. Ahlborn (UBC), J. Harnad (Concordia), M. A. Walton (Lethbridge), T. A. Osborn (Manitoba), D. A. Goodings (McMaster), and J. W. G. Darewych (York). In addition, W. E. Baylis at Windsor is developing alternative formulations of the laws of physics in terms of the Pauli algebra with the aim of achieving new unifications and insights, and L. Ballentine at Simon Fraser is well-known for his work on alternative formulations of quantum mechanics.

Of a similarly general nature is the widely-cited work of Y. P. Varshni (Ottawa) on the development of supersymmetric quantum mechanics to extend the range of potentials for which exact eigenvalues can be calculated. Another topic of great current interest is the behaviour of classically chaotic systems and their quantum correspondence (Ali, Ballentine). The general principles derived from these studies are applicable to broad classes of systems displaying chaotic behaviour at both the classical and quantum levels.

Closely related to the above is the ongoing development of the methods of mathematical physics. Contributions of the Montréal group of mathematical physicists organized around the Centre de Recherches Mathematiques (A. M. Grundland, J. Harnad, V. Hussin, Y. Saint-Aubin, R. T. Sharp, L. Vinet, P. Winternitz and others) have been widely recognized internationally. The main contributions of this group include:

- The development of efficient methods for studying deformations and contractions of Lie algebras and their representations, for classifying subalgebras of Lie algebras and for classifying and identifying Lie algebras themselves. Lie algebras form the mathematical basis for exploiting the symmetries of nature, and as such have great fundamental importance.
- Basic contributions have been made to the theory of aperiodic structures with long range order (quasilattices, quasicrystals ...).
- The most powerful algorithms known for providing computational information on the representations of Lie algebras of finite and infinite dimensions have been developed by members of the Montréal group.
- There is a strong concentration on the theory of finite and infinite dimensional integrable systems, on special function theory, in particular q-special functions related to the representations of quantum groups and integrable models in relationship with statistical mechanics and conformal field theories.
- A related theme is the study of the symmetries of differential equations and an extension of symmetry methods to obtain solutions of linear and nonlinear difference equations.

A team from the Centre de recherches de mathématiques and UQAM has received a NSERC Collaborative Grant. This grant was awarded during the fall of 1995 for a proposal entitled *Algebraic Combinatorics and Quantum Integrable Models*. The team consists of: L. Vinet (CRM, team leader), F. Bergeron (UQAM), N. Bergeron (York), R. Floreanini (INFN, Trieste), A. Garsia (UC at San Diego), J. Harnad (Concordia), D. Levi (Univ. di Roma III), C. Reutenauer (UQAM), Y. Saint-Aubin (CRM) and P. Winternitz (CRM). The project lies at the interface of theoretical physics and combinatorics, and focuses on integrable systems and special function theory. The main objective of the program is to study the various algebraic and combinatorial aspects of the Calogero-Sutherland model and its generalizations. This will most likely lead to significant advances in many important mathematical and physical areas (condensed matter physics, special function theory, conformal field theory, representation theory, algebra, integrable systems, etc.) that this model connects in an extraordinary way.

Elsewhere in Canada should be mentioned the work of Papini (Regina) on the many manifestations and applications of geometrical phases in quantum mechanics, and Soteros (Saskatchewan) on the application of lattice models of statistical physics to the properties of polymers. An important feature of the latter work is its interdisciplinary nature with extensive interactions with mathematicians, computer scientists, polymer chemists, and biologists. One of the aims is the search for principles of "universality" governing the behaviour of such complex systems, and their topological complexity.

8.3.1 Relationship to Mathematics

The boundary between mathematics and physics has become more and more diffuse in the last decade. The roles of functional analysis, differential equations, symmetries and group theory have expanded dramatically, and new chapters of mathematics have become crucial for physics: differential geometry, new structures discovered by algebraists, combinatorics, chaos and bifurcation theory, etc. Conversely and during the same period, many developments in pure mathematics have been triggered by ideas and concepts introduced by physicists. A striking indication of this cross-fertilization is the fact that the U.S. physicist Edward Witten won the Fields Medal in 1990.

This symbiosis can be seen in the research done in Canada as well. For example, Two of the young stars working together on problems related to conformal field theory (M. Walton (Lethbridge) and T. Gannon (York)) are funded by the GSC's for General Physics and Mathematics respectively. Canadian mathematical physicists (of GSC-29) work on algebraic structure (infinite dimensional algebras, quantum groups, supersymmetric extensions, etc.), classical and quantum integrable models, their symmetries and conformal field theories, and statistical physics. These are exactly some of the most active research topics pursued at the leading research institutes around the world, either in mathematics or physics departments. Large conferences are organized on these very topics yearly. The fact that Canadian mathematical physicists are often invited to participate as plenary session speakers, or as conference organizers, speaks for their reputation and the importance of their work on the international scene.

9 Strengths and Weaknesses of Physics in Canada

The material presented in this and the following sections represents a blend of the conclusions that can be drawn from the Overview of Canadian physics in the previous section, together with specific responses to the questionnaires.

9.1 General Physics

9.1.1 Strengths

The overview and historical perspective presented in the previous section shows that much of the current activity in General Physics can be traced back to the early Canadian strengths in classical spectroscopy and optics. This has led naturally to the current strengths in atomic and molecular physics, optical physics, plasma physics, and atmospheric/space physics, as discussed further below. As emphasized in the previous section, these are not independent fields of study, but rather they are linked together by common bonds of experimental technique and underlying theory. For example, plasma physics could not progress without the input of new atomic and molecular data and the ever increasing capabilities of lasers. In fact, lasers and their many varied applications provide a common link relating much of the work being done.

The overview also shows that the topics covered by General Physics deal with the energy scale of everyday phenomena. For this reason, there is a rich variety of applications in areas such as photonics, plasma processing, optical communications, and many other interdisciplinary topics. This is further discussed in Sect. 5.4 (p. 32).

Table 3 shows the distribution of funding by subfield for GSC-29, together with the number of researchers supported in each area (including group grants). Although there is considerable overlap in the definitions, the various subfields are defined as follows:

- AM – Atomic and Molecular physics, including spectroscopy, atomic and molecular structure, collisional interactions and dynamics.
- PL – Plasma physics, including controlled fusion and laser-plasma interactions.
- LA – Laser physics particularly focused on laser development as opposed to laser applications.
- OP – Optical physics, including quantum optics, optical devices, fibre optics, image processing, photonics, laser applications, and nonlinear phenomena.

Table 3: Funding for General Physics (GSC-29) by subfield, and numbers of researchers supported.

	Experiment		Theory		Total	
Field	No.	Amount	No.	Amount	No.	Amount
AM	48	1 387 366.	18	340 700.	67	1 728 066.
PL	19	854 700.	5	91 500.	24	946 200.
LA	5	53 600.	0	0.	5	53 600.
OP	19	651 500.	3	67 000.	22	718 500.
FD	0	0.	12	195 900.	12	195 900.
MP	0	0.	12	253 100.	12	253 100.
Total	91	2 947 166.	50	948 200.	141	3 895 366.

Table 4: Funding for Atmospheric Physics/Space Science (GSC-17) by subfield, and numbers of researchers supported.

	Type A		Type B		Total	
Field	No.	Amount	No.	Amount	No.	Amount
AP	38	1 193 500.	20	517 000.	58	1 710 500.
AT	21	737 000.	10	340 000.	31	1 077 000.
OB	28	804 000.	0	0.	28	804 000.
PS	3	31 000.	0	0.	3	31 000.
GR	0	0.	33	1 145 900.	33	1 145 900.
Total	90	2 765 500.	63	2 002 900.	153	4 768 400.

- FD – Fundamental theory of a broad and general nature, including field theory, quantum electrodynamics, chaos, nonlinear systems, and statistical mechanics.
- MP – Mathematical Physics, including topics of a general mathematical nature such as group theory, and the solution of systems of differential equations.

In addition, each subtopic is divided into theory and experiment. A detailed breakdown into individual research programs is given in Tables 34 (p. 132) and 35 (p. 138), ordered by institution and field respectively.

Table 3 shows that AM receives the largest block of funding, followed by PL and OP. The direct support of laser development (LA) by NSERC through GSC-29 is relatively small, but this represents only a small part of the total support in Canada. For example, the Ontario Laser and Lightwave Research Centre (OLLRC) had a total 1996 budget of $4,535,504 through the Ontario Centres of Excellence program, which exceeds the total annual budget of GSC-29. This amount is more than doubled by additional industrial and government (NSERC and non-NSERC) support. Some of this funding goes to laser development.

In addition to the NSERC operating grants shown in Table 3, 28 of the 52 respondents supported by GSC-29 reported additional sources of funding for a total of $5 020 291. This indicates that a great deal of research activity is taking place that is not funded by NSERC.

The table also indicates a solid level of support for both FD and MP. This level of support is appropriate since fundamental advances of a general mathematical or theoretical nature can have far-reaching consequences, but it is difficult to find alternative sources of funding for this type of work. Overall, there appears to be an appropriate balance between theory and experiment in terms of both funding levels and numbers of researchers.

Table 4 shows the corresponding distribution of funding by subfield for atmospheric physics and space science. The field codes are:

- AP – Astrophysics, divided into galactic research (Type A), and stellar research (Type B).
- AT – Atmospheric physics, divided into observational programs (Type A), and theoretical programs (Type B).
- OB – Observational astronomy.
- PS – Planetary and (near) space physics.
- GR – General relativity, gravitation, and cosmology.

Table 5: Questionnaire responses identifying current areas of strength in Canada for Physics research.

Area of Research	Number	Principal Centres
Optics, lasers, nonlinear phenomena	12	INRS, Laval, Sherbrooke, Toronto, York, Western, Windsor, Alberta, NRC
Atomic and molecular physics	9	Memorial, UNB, Laval, Toronto, York, Western, Windsor, Manitoba, Alberta, NRC
Astrophysics and space research	8	Toronto, York, Saskatchewan
Cosmology, black holes, general rel.	4	Toronto, Alberta, UBC
Plasma physics	2	INRS, Toronto, Saskatchewan, Alberta
Medical applications	1	Carleton, Laval, Sherbrooke

A detailed breakdown into individual research programs is given in Tables 36 (p. 144) and 37 (p. 150), ordered by institution and field respectively.

Table 4 shows that astrophysics (AP) receives the largest block of funding, followed by general relativity (GR) and atmospheric physics (AT). The relatively high level of funding for GR does not include additional funding from the Mathematics GSC. It indicates the high stature of this field in Canada.

In addition to the NSERC funding shown in Table 4, the ten respondents in the area of atmospheric physics and space science reported additional funding totaling \$2 708 900. Those in general relativity reported an additional \$156 580.

As shown in Table 5, The areas with substantial funding levels are reflected by the areas identified as "current areas of strength in Canada for physics research" in the questionnaire responses. The numbers in the table should not be taken too literally because respondents tended to identify areas related to their own work as "strong", but the list of topics is at least representative of the current areas of strength supported by GSC-29. With reference to optics and lasers, applications to photonics and telecommunications were frequently mentioned, together with their economic importance as well as contributions to fundamental science. Areas mentioned which are outside the scope of this report are not included because they are too few to be representative.

The overall strength of the field is indicated by the high level of publication by its members. Table 6 shows the total numbers of publications reported by the respondents to the questionnaire, and the numbers for the past five years. Of the 67 respondents who gave numbers, the median total number of publications is 70, and 19 respondents reported 100 or more publications. For the last five years, the median number is 17, and 16 respondents reported 25 or more publications. These numbers indicate a high level of activity in the field.

In addition to numbers of publications, the significance and impact of the work funded by GSC's 17 and 29 is indicated by the many international honours and awards received by the grantees, as summarized in Appendix B. The Appendix also lists various editorial positions or other leadership positions of an international or interdisciplinary nature that are held by the grantees in recognition of their work. As particularly significant indicators of international recognition, the International Conference on the Physics of Electronic and Atomic Collisions (ICPEAC) was hosted in Vancouver in 1995, and the International Conference on Atomic Physics (ICAP) will be hosted by Windsor in 1998. These are the two most important conferences in the world. Also, the Canadian Division of Atomic and Molecular Physics (DAMP), and the American Division of Atomic, Molecular, and Optical Physics (DAMOP) have established a six-year cycle of joint

Table 6: Questionnaire responses giving total numbers of publications, and publications in the last five years.

Total publications		Last five years	
Number of publications	Number of responses	Number of publications	Number of responses
0– 9	3	0– 4	4
10–19	4	5– 9	9
20–29	6	10–14	14
30–39	6	15–19	9
40–49	9	20–24	14
50–59	2	25–29	4
60–69	3	30–34	2
70–79	7	35–39	2
80–89	4	40–44	4
90–99	4	45–49	1
100–109	3	50–54	1
110–119	3	55–59	0
120–129	2	60–64	0
130–139	1	65–69	2
140–149	3		
150–159	2		
160+	4		

meetings, beginning with Windsor in 1989, Toronto in 1995, and the University of Western Ontario in 2001.

Also mentioned in the responses as "strengths" were the following items:

- Canadian physicists maintain strong international links, and enjoy a high degree of recognition on an international scale in the above areas. This helps greatly in enabling leading edge research.
- Much of the strength comes from individuals working in their various subfields, rather than targeted group projects.
- The diversity of topics covered provides the flexibility to respond to new opportunities as they arise. Since the diverse topics fall within common bounds of technology and theoretical foundations, they form an organic whole capable of flexible adaptation to change. This clearly represents a strength, rather than a lack of focus.
- Canada does an outstanding job of training students for both research and nonresearch jobs. Many of our students go on to become world-class leaders in laboratories world wide. The "small physics" nature of the topics covered allows students to become involved with all aspects of a project from construction of the apparatus to data collection and analysis.

In summary, the strengths flow largely from a unified web of topics beginning with laser technology and continuing with its applications to the study of atomic and molecular phenomena, plasma interactions, surface physics, and nonlinear interactions of light with matter, together with the theoretical underpinnings for all of these topics. Since all of this occurs on the energy scale of everyday phenomena, there are wide-ranging industrial and interdisciplinary applications in areas such as photonics, controlled fusion, plasma processing, telecommunications, time and frequency standards, atmospheric and space physics, and medicine. These branches of physics are not only fundamental in their own right, but they also provide the enabling technology for many other industrial and interdisciplinary applications. They form an organic whole capable of flexible adaptation to new opportunities.

9.1.2 Weaknesses

Aside from specific topics that are under-represented in Canada, the most common replies to the questionnaires indicated that there were insufficient funds to remain competitive in the areas identified in Sect. 9.1.1 as areas of strength. It is becoming increasingly difficult for small experimental groups to maintain state-of-the-art laboratories. Specific comparisons were made to the superior cash flow of researchers in Germany or the U.S., enabling them to acquire new equipment without having to wait a year for an equipment grant application to be approved. This hinders the very flexibility that should be a strength of Canadian physics. There is clearly a danger that Canada will lose its competitive edge even in the current areas of strength. A consequence will be that Canadian research will become relegated to marginal areas of limited interest elsewhere.

Concerning specific topics that are under-represented, the 1994 FAMOS report on the future of AMO science in the U.S. [5] identified three topics for special mention: (i) lasers, (ii) manipulating atoms, and (iii) carbon clusters. Of these, Canada has mounted a significant effort only in the area of lasers. The manipulation of atoms through cooling and trapping (leading, for example, to Bose-Einstein condensation) is developing very rapidly in the U.S. and Europe, but there is little activity in Canada, with the exception of a program just beginning at Toronto (Steinberg) and at NRC (Gagné). The recent demonstration of an atom laser by Wolfgang Ketterle at MIT is opening dramatic new possibilities for the control and manipulation of atoms in the same way that lasers control and manipulate light. The potential applications of this new paradigm in atomic physics could be as important as the laser itself in areas such as ultrahigh resolution lithography for microelectronics. It is a natural area in which Canada should be making a major contribution. A failure to provide adequate funding for this will exclude Canada from participating in the exciting possibilities for scientific applications and industrial spin-offs.

Similarly, the intense activity elsewhere in the world on carbon clusters is mirrored in Canada only by some initial work at Windsor on electron scattering by clusters (McConkey), together with theoretical and experimental work supported by the Chemistry GSC at Waterloo.

Concerning plasma physics and the inertial confinement fusion program, Canada's earlier impact in this area is now declining as the needs for lasers of higher power and shorter wavelength escalate beyond the reach of funding in Canada (see Sect. 5.2, p. 30). Similarly, the magnetic confinement fusion programs are under severe funding pressure, as also discussed in Sect. 5.2, and may come to a premature end. Plasma physics is in danger of becoming weak if the numbers of researchers fall below a "critical mass". Even though much of the earlier ICF and MCF work is now being redirected toward plasma applications (see Sect. 5.4, p. 32), the viability of these groups is in danger of being lost or marginalized to peripheral topics.

Other points mentioned in the questionnaire responses include:

- The lack of a synchrotron radiation facility in Canada. The Wisconsin beam line is a poor substitute for a national facility.
- Inadequate supercomputer facilities. This point was frequently mentioned, particularly in connection with studies of nonlinear dynamics and chaos.
- Quantum computing is potentially very important, but few people are working on it in Canada.

- The rapidly developing and important area of Bose-Einstein condensation and atom lasers is severely under-represented in Canada.
- Medical physics is too scarce, considering the potentially important contributions that could be made.
- Large scale projects take up too much money relative to their impact. The research dollars would be better spent on the "small science" that is done best in Canada, rather than measuring ourselves with an American yardstick.
- There is generally a lack of incentives or opportunity for new faculty members throughout the university system.

In summary, dramatic advances are in progress elsewhere in the world. Whole new fields of development such as atom lasers and quantum computing have suddenly sprung into being, together with the relentless advance of optical lasers and their applications. The implications are so profound that they are changing the very meaning of the term "atomic, molecular and optical physics". However, Canada is barely participating in these developments, and will soon be left far behind at current funding levels. Not only will opportunities for industrial spin-offs and engineering applications be lost, but our graduates will be ill-equipped to compete on the international job market.

9.2 General Relativity and Gravity

The areas of strength in general relativity and gravity research are surveyed in Sect. 7.3 (p. 44), and future areas of growth are discussed in Sect. 11.4 (p. 83). The group of researchers who fall under this area of research include some of the top theorists in Canada. For example, there are two fellows of the Royal Society of London, five of the Royal Society of Canada, two winners of the Killam Prize in Natural Sciences of the Canada Council, five winners of Stacie Prizes and Stacie Fellowships and other honours. The group includes all of the Canadian members of the Cosmology and Gravity program of the CIAR (see footnote in Sect. 7.3, p. 44).

The strength of a part of this group is also reflected in the NSERC operating grants, in which about ten from Table 2 (p. 45) are in the top 10% of grants in physics and astronomy. The distribution of NSERC grants for this area is further discussed in Sect. 12.1.1 (see especially Figure 6, p. 88).

The above researchers bring in other monies as well. For example, the the CIAR has a budget of over $800K for the program in Cosmology and Gravity, all of whose Canadian members belong to this community. It is interesting to contemplate in these days of "industrial relevance" that the major funding in the early days of this program came from Lac Minerals Corporation, and now a major donor is Imasco.

In the links to observational cosmology and astrophysics, we at present have significant strength in Canada. However, the fragility of this strength is evident in the recent loss of top people from CITA (see Sect. 7.3, p. 44). Furthermore, it is a field which is attracting increasing competition, especially from the U.S., and a strong response from the Canadian system will be needed. As an example, the University of Pennsylvania has hired five people in two years in this area. The constant erosion across the country of university salaries makes recruitment extremely difficult.

One of the weaknesses in the field in Canada has often been the relative isolation of the researchers. One often finds individuals in this field installed singly at universities, with little contact with each other. The Canadian Association of Physicists and CITA have over the past number of years been helping to alleviate this isolation by sponsoring a yearly meeting in General Relativity.

However despite these attempts the impact of these isolated researchers on the international community has often not been commensurate with their number. A second weakness is that there are no string theorists in Canada.

10 Success Stories in General Physics

This section first highlights a few of the scientific success stories achieved by Canadian researchers in the areas covered by General Physics. Further success stories for General Relativity and Gravitation are collected together with other material on this topic in Sect. 7.4 (p. 46). The aim here is to give a nontechnical overview of the motivations for the work and the significance of the results obtained. This is followed by Sect. 10.2 (p. 72) describing some of the industrial spin-offs that have resulted from this work. Industrial spin-offs also play a prominent role in atmospheric physics, as discussed separately in Sect. 6.1.1 (p. 37). In the interests of brevity, only a representative sample of cases is included. There are many other equally meritorious stories that could be told.

The division of subject matter into "basic physics" and "applied physics" is purely a matter of convenience for the reader. It is important to stress that there is a broad continuum ranging from fundamental principles to their applications, and that good science is being done at both extremes, often by the same research group. This is further discussed in Sect. 20.3 (p. 107).

10.1 Success Stories in Basic Physics

From Black Hole Evaporation to Quantum Computing. General relativity and gravity research exemplies the way in which the ideas and techniques of theoretical physics can be taken from one area and applied to a wide variety of other problems. It is typical that advances in theoretical physics have an impact not just in one or two areas of physics, but across a broad range of studies in otherwise unrelated fields.

An example of this broad ranging activity in theoretical physics is the work of Unruh at UBC. He made his initial mark on the field in attempting to understand the phenomenon of black hole evaporation first discovered by Hawking. He showed that the acceleration of a body produces thermal features due to its interaction with the vacuum fluctuations of the radiation field. This effect, which could have been discovered at any time since the 1930's when quantum field theory was invented, has found application in areas as diverse as explaining spin depolarization in particle accelerators, and as a possible source for the high temperatures seen in sonoluminescence, areas far from the study of black holes where the effect originated. That same effect was crucial in describing the thermodynamic behaviour of black holes, and explicitly demonstrating how black holes obey the second law of thermodynamics.

Using ideas from hydrodynamics, he showed how fluid flows could be used to model and understand the behaviour of quantum fields near black holes (see for example the article by L. Susskind in the April 1997 issue of Scientific American). If the fluid flow becomes hypersonic, the surface at which the flow velocity equals the velocity of sound acts as an exact analog of the horizon of a black hole. While no quantum theory of gravity exists to describe the short distance behaviour of the gravitational field, the atomic nature of matter provides short distance cutoffs for the phonon fluctuations in the fluid flow. Thus the thermal emission spectrum from such sonic analogs for black holes is unaffected by the cutoff provided by the atomic nature of matter. This suggests that also in the black hole case, the thermal emission is primarily a low energy phenomenon, rather than arising from the ultra-high energy range, as suggested by usual derivations of the Hawking effect. That these results appear to be in conflict with recent string theory work on the origin of the entropy of black holes simply adds to the mystery of black hole thermodynamics. There is no doubt that the resolution of this conflict will immeasurably deepen our understanding of both quantum phenomena and gravity.

As is usual in modern theoretical physics, such concerns with understanding the basic issues surrounding quantum phenomena can have immediate application in totally disparate areas. Three years ago, Peter Shor discovered that quantum computers could solve certain problems much more efficiently than any classical computer could. However, Unruh quickly realised from his work in understanding quantum gravity that the scheme suffered a severe difficulty. Interactions with the external world would destroy the coherence needed for such a computer to work. While the results were extremely pessimistic for the realisation of such proposals, they helped to trigger the surprisingly successful search for quantum error correction techniques for such computers (first found by Shor). In fact, some of the dominant players in the field of quantum computation were originally trained in quantum gravity (e.g., Laflamme, originally from Laval, a student of Hawking, and a postdoctoral fellow of Unruh). Examples like these abound in all areas of theoretical physics. They are a key reason for its intellectual vitality and potential for future insights.

Probing New Physics with Helium. The modern era of quantum mechanics began in 1925 with the introduction of the Schrödinger equation as the fundamental equation governing the behaviour of atoms and molecules. The Schrödinger equation represents the extension of classical Newtonian mechanics to microscopic systems where the wave nature of matter becomes of dominant importance. Solutions for the simplest case of the hydrogen atom were quickly found in 1925 to be in reasonable agreement with measurements of its various properties. Since then, the next most complicated case, the helium atom, has posed a special challenge to theorists because it is the simplest atomic system for which exact solutions to the Schrödinger equation are not known. Its predictions for the behaviour of helium (and all more complicated atoms and molecules) can therefore only be approximated. With its nucleus plus two "planetary" electrons, the helium atom is the quantum analogue of a classical "three-body problem," such as a solar system with two large planets. This has equally defied the best attempts of mathematicians to find exact solutions since the time of Newton. For such systems, the regular elliptical orbits of a single isolated planet are replaced by complex nonperiodic orbits that over long periods of time appear to be chaotic.

Approximation methods for solving the helium problem have gradually improved over the years, but until recently, they fell far short of modern spectroscopic accuracy for measuring the frequency of atomic transitions and other properties. Consequently, no one could state for sure whether or not the Schrödinger equation (plus numerous corrections for the effects of relativity and quantum electrodynamics) provides an exact description of nature for atomic systems more complicated than hydrogen. This situation has now changed dramatically with the advent of new approximation methods introduced by Drake and his students at the University of Windsor. Solutions can now be calculated which are essentially exact for all practical purposes in that the error is much less than the experimental uncertainty. The key to the improved accuracy is the use of mathematical approximating functions which provide a better physical description of the distance scales involved in the electronic orbits. The method is called *variational* because the scales are varied in a systematic way to obtain the best possible solution. Accuracies of better than one part in 10^{16} for the entire spectrum of atomic energies are now typical.

For electronic states with high angular momentum, a second method requiring nothing more than simple hand calculations has recently been perfected by Drake and others. It is based on the appealing physical model of an outer planetary electron far from the nucleus slightly distorting the orbit of the inner electron. The energy of the outer electron then changes slightly due to the distortion. The results agree precisely with the variational calculations when the angular momentum becomes high enough. Thus the two methods provide strong support for each other. Taken together, they cover the entire spectrum of helium.

The new opportunities provided by these results have been recognized by experimentalists around the world who are now performing very high precision atomic frequency measurements for comparison with theory. For example, table-top laser measurements at Harvard, Yale, North

Texas, Florence, and Strathclyde are able to use these results in a determination of the nuclear radius by comparing different isotopes of the same element. These, and other experiments at NIST, Paris and York (Hessels) provide the first fundamental tests of quantum electrodynamics in atoms containing more than one electron. In fact, the accuracy now rivals traditional measurements of these effects in hydrogen. The high precision theory in effect provides researchers with a much more powerful microscope to reveal new physical effects that were previously obscured by computational uncertainties.

The forefront of research is now moving from the three-body problem to atoms or molecules containing four particles such as lithium or H_2. Although the complexity of "essentially exact" calculations increases very rapidly with the number of particles, and current standards of accuracy are much lower, results exceeding spectroscopic accuracy have recently been achieved for the low-lying states of lithium (Yan and Drake). This in turn is providing the motivation to improve the state-of-the-art for the stability and frequency control of lasers so that measurements of comparable precision can be made. In collaboration with a group at the GSI accelerator, Darmstadt, this combination of theory and experiment will be used to probe the properties of exotic "halo" nuclei such as ^{1}1Li through their influence on atomic energy levels.

New Phenomena in Laser-Matter Interactions. At the opposite extreme from very high precision frequency measurements are the new phenomena that appear when the laser intensity is made very high. By the use of various nonlinear techniques, it is possible to compress all the energy of a standard laser pulse into an extremely short time interval so that, during that brief period, the intensity (brightness) of the laser light becomes extraordinarily high. In fact, the intensity becomes so high that the strength of the oscillating electric field of the laser light becomes comparable to the electric fields binding electrons to atoms and molecules. Under these conditions, the physics of atom-laser interactions enters an entirely new regime that cannot be treated by traditional methods. It is easy enough to see that unusual things begin to happen, but it is much more difficult to unravel the details of what is observed and provide an explanation for them.

S. L. Chin and his collaborators at Laval and NRC have played a leading role in identifying the new phenomena that appear in this high intensity regime and constructing models to account for them. A key breakthrough occurred in 1985 with his first observation of *tunnel ionization.* It had long been known that several photons could combine their energies to eject a single electron (multiphoton ionization), but this explanation could not be applied to the long wavelength CO_2 laser radiation used in the experiments because more than 100 photons would have been required to eject a single electron. Instead, the electrons were escaping from the atoms by the quantum mechanical process of "tunneling through" the potential barrier formed by the combined effect of the atomic potential, and the time-dependent laser potential. The success of this experiment depended on their advances in the stabilization of high intensity laser pulses so that reproducible results could be obtained. These stabilization techniques are now being widely adopted in other laboratories.

Their identification of a new ionization mechanism has led to a long series of experiments in which tunnel ionization, or alternative ionization mechanisms, play an important role. For example, subsequent work by Chin with Corkum at NRC focussed on the very high harmonic generation (i.e. light at 100 or more times the frequency of the incident pulse) that occurs when a high intensity laser pulse passes through a gas. In their model to explain this process, an electron first escapes from the atom by tunnel ionization. It is then accelerated by the oscillating laser field, and ultimately driven back to the parent ion where it can recombine, accompanied by the emission of a high energy photon. This model has been very successful in explaining the observed spectrum of harmonic frequencies, and especially the high energy cut-off at about three times the oscillation energy of a free electron in the laser field (the ponderomotive energy). In related experiments with molecules, the returning electron can recombine with the parent molecular ion in such a way that the resultant molecule is unstable and dissociates (dissociative recombination). They have also demonstrated that for light molecules such as H_2 and D_2, there is a competing "bond softening" mechanism in which the molecular bond is directly altered (weakened) by the photon field, and that as the bond stretches, there is a critical bond length at which enhanced ionization takes place.

These results are significant on several different levels. First, they provide critical guidance in the construction of realistic theories for the interaction of intense laser radiation with matter. The well known theories for the emission and absorption of radiation are of little use in this regime of high intensities, and the systems are sufficiently complex that full three-dimensional models are intractibally difficult to solve directly. Many of the effects were first observed in the laboratory before they received a theoretical explanation. Others, such a tunnel ionization, were postulated as possible mechanisms, but there was little confidence that20they played any significant role until they were confirmed experimentally. The parallel development of theory and experiment is therefore essential to the progress of the field. Second, these advances in our understanding of strong interactions between lasers and matter can be applied to many other areas20such as plasma processing and the production of ionized plasmas by intense lasers. Finally, it opens new possibilities for the direct laser control of chemical reactions, especially through the techniques of coherence control as discussed in the following paragraph.

Directing Processes with Lasers. The hallmark of quantum mechanics is that matter is described by a matter wave and that, just as with light waves, matter waves can interfere with one another to produce either constructive or destructive interference, depending on the relative phase of the waves. If a peak aligns with a peak, then the amplitudes add, whereas if a peak aligns with a valley, then the amplitudes tend to cancel. The same reasoning applies when more than one path leads from a given initial state of the system to the same final state. The amplitudes for the two paths can either add or cancel, depending on the relative phase. Waves (or paths) with a definite phase relationship are said to be *coherent*. Since laser radiation itself is coherent, it provides a means to control the relative phases of different paths, and thereby turn the overall process on and off.

The coherence control of processes is a relatively new area whose possibilities are just beginning to be explored. A remarkable demonstration has recently been given by van Driel (U. of T.) who showed that the direction of photoelectric currents in a semiconductor can be controlled by the relative phases of optical excitation of the material. The long-range possibilities for this are profound indeed since it provides an optical alternative to the application of external biasing potentials to control currents in semiconductors. Similar effects have been observed by Corkum and co-workers in the direction of photoelectron emission from gases. It is clear that in the future, this will develop into a powerful new technique for the control and manipulation of matter by lasers.

X-ray Pulses from Lasers. A long-range goal of laser research is the construction of a short-pulse x-ray laser that could sit on a table top in any laboratory. This would extend all the capabilities of current laser sources into the x-ray region of the spectrum, with many applications in areas such as chemical analysis, medical diagnostics and x-ray holography. However this is still far from realization. In the mean time, an important step in the direction of possible applications been achieved by a team led by Jean-Claude Kieffer of INRS-Énergie et Matériaux. They have developed an incoherent source emitting a short pulse of x-rays from a very small spot on the surface of a metal such as aluminum.

Their technique begins with a subpicosecond pulse of light from a table-top terrawatt glass laser which is frequency doubled to produce green light and then brought to a sharp focus at the metal surface. This brief pulse of energy vaporizes and completely ionizes some of the metal to produce a small disk of hot metal plasma with near-solid density. However, the production of a useful pulse of x-rays from the metal plasma requires careful design based on a deep understanding of the physics involved in high intensity laser-plasma interactions, and the way in which the plasma disk evolves with time. Much of this understanding came from previous work related to laser-driven thermonuclear fusion and from x-ray laser studies.

The key to the efficient production of useful x-rays is to keep the spot size small and the laser pulse sharply defined in time. A small spot size is desirable not only because this is a prerequisite for imaging and scattering diagnostics, but also because it implies higher intensity at the plasma disk and hence better x-ray conversion. The laser pulse must therefore be of high quality to allow focusing to a small spot. Apart from any time resolution requirement, a short laser pulse duration is necessary to ensure that the hot plasma formed near the surface has not the time to spread out and enlarge the x ray source size while the laser is on and the plasma is hot. A rapid rise of the pulse to its full value is essential to avoid the formation of a weak low density plasma in front of the main plasma disk. Here, the step of frequency doubling plays an important role because it avoids having any laser energy arriving before the main pulse. However, the most significant point was their prediction that as the laser intensity approached the very high but attainable value of 10^{17} w/cm^2, the very radiation pressure of the light itself would prevent the hot plasma from exploding away from the target surface, and that is indeed what happened.

Since these x-ray pulses are produced from a table-top terrawatt laser, they are automatically synchronized with the laser pulse itself. This makes them particularly useful in experiments of the pump-and-probe type where a process is initiated (pumped) by the laser pulse, and the results analysed (probed) by the x-ray pulse. As an example, they have observed the laser-driven breakup of the SF_6 molecule with subpicosecond time resolution. The greatest challenge for the future is to reach the femtosecond regime where the evolution of chemical processes can be followed in detail. In the mean time, the most interesting applications lie elsewhwere in areas such as medical diagnostics. A current pilot project is under way on angiography of the heart with doctors from SUNY (Syracuse) under a grant from the U.S. National Institute of Health. Here it is the small spot size compared with standard x-ray sources that is decisive in producing high quality images. The chief technical challenge now facing this application is to maintain or improve the x-ray performance per pulse while increasing the repetition rate to that necessary for eventual clinical use.

New Techniques in Atomic and Molecular Collisions. Collisions between electrons, photons, atoms and molecules are the basic events controlling the rates of all physical and chemical processes, ranging from the formation of a laboratory plasma to the complex dynamics of the earth's atmosphere and astrophysical sources. Even the simplest case of an energetic electron colliding with an atom can give rise to a huge variety of excitation and ionization processes. Collision theory plays an essential role in extending and extrapolating what can be measured directly in the laboratory, in addition to providing a fundamental understanding of the basic physics involved. However, the various approximation methods must first be checked against benchmark laboratory measurements for a number of key processes. As theory develops and improves, it can be used with greater confidence to calculate data for more exotic species.

The greatest challenge to theory is provided by the most detailed measurements involving the angular distributions and polarizations of the scattered particles. McConkey (Windsor) has succeeded in obtaining the necessary benchmark data by the electron impact excitation of the noble gases. This required the development of new polarization analysis techniques (particularly for circular polarization) which could be used in the vacuum ultraviolet spectral region where the resonance transitions of the noble gases lie. Measurements of the polarization of the resultant radiation have provided very sensitive tests of scattering theory at the most basic level of detail possible. These results were of key importance in stimulating new theoretical developments by McEachran and Stauffer (York) and others because no theory then available could adequately describe the angular momentum transfer responsible for the polarization phenomena. The subsequent efforts by theoreticians have now brought theory and experiment into good agreement. Currently, Zetner (Manitoba) is extending these benchmark measurements to target atoms in excited states created by laser excitation. These difficult and challenging experiments are opening up a new area for exploration where little is known about scattering amplitudes and relative phases.

More complex scattering events involving, for example, the dissociation of molecules into their constituent atoms, introduce additional technical difficulties in a full characterization of the process being observed. Molecular dissociation is a vitally important process as the initiator of chemical reactions in the upper atmosphere and in many other situations. To quantify and properly understand the dynamics of the dissociation process, it is necessary to define the dissociation fragments together with their kinetic and internal energies. This is necessary because there is often a large number of possible molecular states leading to dissociation, making an accurate characterization of the process difficult. Of particular difficulty are the situations where the fragments are not charged or excited, and so conventional mass or optical spectroscopic techniques cannot be applied.

To surmount these problems, McConkey has developed a number of fragment-specific detection techniques. One that is of particularly important to studies of the aurora is a method for selectively detecting oxygen in the metastable ^1S state. Radiation from this long-lived state produces the auroral green line in the upper atmosphere, but in the laboratory the atom collides with the walls of the apparatus and is lost before it has a chance to reveal its presence by radiation. McConkey solved this long-standing detection problem by his discovery that metastable oxygen atoms can be trapped in a cold matrix of solid xenon where the atoms thermalize, form an XeO eximer and promptly radiate, thus allowing detection. This method has now led to precise measurements of the production of metastable oxygen from many oxygen-containing molecules, and especially from processes responsible for the auroral green line.

10.2 Success Stories in Applied Physics

The NSERC Research Grants Program in Physics can offer numerous examples of how long-term research results can be translated into commercial opportunities. Many of these involve the transfer of processes or instrumentation developed during the course of research. In some cases, investigators have spun off their own companies to further economic development in Canada. This section describes a few notable examples.

Bomem Inc. is a multinational company selling Fourier transform interferometers. These are widely used as standard spectroscopic instruments for diagnostics in a host of applications. The Company was started by Henry Buijs who is a product of solid AMO spectroscopic training at the University of Toronto and UBC, before his first commercial instrument for Fourier transform spectroscopy was developed at Laval. The instrumentation is a direct product of his early research projects to monitor infrared emissions from atmospheric sources with particular application to the photochemistry of the stratosphere.

Electrophotonics. For almost ten years Professor Measures and his students at the Institute for Aerospace Studies, University of Toronto have been exploring ways in which fibre optics can be used as environmental sensors. For example when fibres are embedded in solids they can become highly sensitive diagnostics of pressure, strain and temperature. This occurs through alteration of light transmission, polarization or frequency. These "smart sensors" are finding a receptive audience in diverse areas of engineering technology. Electrophotonics, a company spun off from Professor Measures' work approximately five years ago, is growing rapidly in sales and prominence to exploit this technology in several areas. In 1993, the City of Calgary commissioned the construction of the world's first highway bridge to test the use of carbon fibre pretesting tendons to replace steel for the precast support girders. Professor Measures group was asked to instrument this unique bridge with a set of structurally integrated fibre-optic Bragg grating strain and temperature sensors. The monitoring of more than 200 000 bridges on this continent alone would justify the development of these sensors.

Work has also proceeded with EDO Canada Ltd. to explore the use of structurally integrated smart sensors in composite cylinders for natural gas vehicles (NGV). This has become somewhat more urgent recently with the explosion of other types of NGV cylinders during pressurization. The use of smart structures is also making inroads in the aerospace industry and the Canadian Space Agency.

Economic impact in these areas is measured in several tens of millions of dollars. In the meantime work continues under the NSERC Research Grants Program to continue to improve the technology and to train students for future scientific and engineering positions in the field.

EXFO. In 1985, the Laval graduates G. Lamonde and R. Tremblay capitalized on their expertise in fibre optics to form the EXFO Electro-Optical Engineering Company. The company quickly took a dominant role in the fibre-optic test equipment industry, and has enjoyed phenomenal growth ever since. The company currently employs over 250 people. EXFO's rise to success is due in part to their manufacture of high quality innovative products such as optical time-domain reflectometers (OTDR's), and optical return loss (ORL) test sets. These products are used to test fibre-optics installations, and they are sold world-wide wherever fibre-optic cable is being deployed. The company has been awarded numerous awards such as the Photonics Spectra Circle of excellence award in 1994, and the Mercuriades Award presented by the Québec Chamber of Commerce. In 1995, the company was rated as one of the fifty best managed private companies in Canada by the Financial Post, and they were awarded a gold medal at the "Gala des 500" in 1995 and 1997 for job creation in high technology industry.

Lumonics. Perhaps the most outstanding success story is Lumonics. During the 1970's, Stoicheff and his group at the University of Toronto were successful in achieving a number of breakthroughs in excimer laser technology that Lumonics in Ottawa was able to commercialize. Lumonics has since grown to become one of the major suppliers of lasers world wide. Lumonics now sponsors an Industrial Research Chair in Laser Physics at the University of Toronto.

Optech. The Optech Company of Toronto is a direct result of research by Professor Carswell (York) aimed at the application of laser radar (lidar) techniques to the remote sensing of atmospheric properties. This includes the development of new lidar systems and methodologies for the acquisition and analysis of atmospheric properties of interest. The success of these ventures led to the spin-off company Optech in 1974. Optech is now a high-tech industrial firm which currently has a staff of about 80 people and does in excess of $10 million in commercial business annually. The company spends over $2 million annually in R and D. Optech exports about 80% of its products. The field is still largely technology limited. As new lasers, electro-optic components, computers etc.

emerge, they will permit improved capabilities and applicability of lidars. In 1993, Optech won the Vaughan Award for outstanding R and D achievements, and in 1994 it won the Canadian Award for Business Excellence and Innovation.

Resonance. The Resonance Company was started modestly by Bill (W.H.) Morrow in the early 80's as a small "incubated" company within CRESS (York University) for the fabrication of space-qualified resonance lamps. These are small rf-driven discharge light sources, most of the radiation from which is emitted from the resonance transition of the relevant atom (e.g. O I, Ar, Kr, etc.). These lamps have many uses in space experiments, and have now been augmented to include many other spectral features. Twenty-two of them are currently flying in various international space missions.

In the mid-1980's, when NSERC started the Strategic Grant program, R. W. Nicholls was awarded one to develop a gas filter remote sensing instrument for measurement of atmospheric contaminants. W. H. Morrow joined him as a research assistant/graduate student in this endeavour. He suggested the development of an instrument based on a rotating digital gas filter correlation wheel, and successfully evolved a family of small rugged digital gas filter correlation radiometers, the first two members of which, GASCOFIL and GASCOSCAN, were developed at York. Depending on the solid-state detectors used, versions of these instruments are sensitive to radiation from the uv to the near ir. The NSERC Strategic Grant was renewed for a second three-year term. The instruments were used to study emission from hydro smokestacks, the Sudbury superstack and the effluents from forest fires, as well as to map SO_2 gas emissions around the road system of greater Toronto.

In the early 1990's W.H. Morrow transferred Resonance to premises in Alliston. He has recently purchased a 5000 sq. ft. building in Barrie where the company is now located.

Sciex. Jay Corr from Professor McConkey's group (Windsor) is a good example of the transfer of basic training in AMO Physics, including a variety of spectroscopies, vacuum technology and digital electronics, to industry. His background from Windsor enabled him to obtain a position in the high-tech firm Sciex (Thornhill, Ontario) specializing in applications of mass spectrometers in medical and environmental situations. Within three months he was able to make a patentable contribution. This is a nice example showing how training and a problem-solving approach can be transferred to industry.

TIR. In 1979, Lorne Whitehead, then a physics graduate student at the University of British Columbia, set about finding an alternative way of lighting his own lab. Whitehead developed a material with a precise prismatic boundary surface that efficiently propagated internally reflected light along its length. The result was the first Light Pipe, based on the principle of total internal reflection. Relatively parallel rays of light are introduced into a hollow prism light guide within a round or square enclosure. Rays that approach the prisms within the critical angle of approximately 30 degrees are refracted back into and along the guide. Other rays escape in a controlled manner, allowing an even distribution of light (within 14% of the average illumination) along a relatively long length. The guiding principle is identical to that of fiber optics, except that in this case, a fraction of the light is encouraged to escape along the length of the pipe.

In 1983, Whitehead established TIR Systems Ltd. (for Total Internal Reflection) to develop a fabrication process now based on specialized materials supplied by 3M. For example, a material known as Scotchlamp Film uses microprisms etched into a thin polymer sheet to create the same effect as the 4 mm rigid walls of the light pipe. In addition to its decorative aspects for the illumination of buildings, the unique advantage of this form of lighting is that the light source can be placed in a remote location from the area being illuminated. Because of this, Light Pipes have found a wide range of applications in areas that are hazardous or difficult to access directly. Some examples include swimming pools, clean rooms, hospitals, dust-filled mines, high humidity conditions or corrosive environments, emergency lighting, airfields, tunnels and subway stations, and special theatrical effects.

TIR Systems has also developed the IRIDIS machine vision lighting system. IRIDIS uses high density discharge sources and linear light guides to deliver high output, uniform and stable light across wide areas. This new type of machine vision illumination system is beginning to supplant aperture fluorescent lamps in line scan applications. Since 1983, the company has grown to its present size of approximately 28 employees with annual sales in excess of $6 million.

11 Future Areas of Focus

The issue of areas of focus for future research should be addressed at two different levels: (i) the level of the individual researcher, and (ii) broad areas of research that deserve special emphasis within the Canadian context.

At the level of the individual researcher, respondents to the questionnaire who addressed this question felt almost unanimously that the individual researcher is the best person to identify the most promising topics for future work. The support of diversity in *basic* research should itself be an important goal because the spin-offs from it are largely unpredictable. The development of MRI in medicine from basic NMR is a good example. The targeting of particular areas of applied research must not be allowed to undermine this enterprise for the expansion of knowledge. Significant breakthroughs rarely occur from "targeted" research. It is important to allow opportunities for new areas to emerge, and to preserve flexibility in the system. New opportunities should be evaluated on a case-by-case basis against each other and against what already exists.

Despite these caveats, it is still possible to identify particularly promising areas for future work that would build on existing Canadian strengths. From our current vantage point, the single most important of these is the new opportunities created by the relentless advance of laser technology and its many varied applications. This theme is more fully developed below in Sect. 11.1 (p. 78). Given suitable funding, Canadian physics is well situated to capitalize on the opportunities it provides. As discussed in Sect. 20.2 (p. 106), a firm foundation already exists for subdisciplinary cooperation between GSC's 28 and 29.

Also consistent with this theme and existing Canadian strengths is the rapidly developing field of computer modelling and simulations of complex systems. Many of the techniques being developed are of broad applicability, but they are particularly needed to understand complex laser-plasma interactions and nonlinear phenomena at high laser intensities.

A second, but not independent area of focus to build upon is the existing Canadian strength in atmospheric and space science, including cosmology and general relativity. This is strongly linked to laser technology because lasers provide one of the prime methods for monitoring atmospheric phenomena, and for measuring the basic atomic and molecular processes needed to understand the mechanisms responsible for both atmospheric and astrophysical observations. Even in cosmology, molecular formation plays an important role in the early universe. One of the two main methods being developed for the detection of gravitational radiation is the U.S. initiative LIGO (Laser Interferometer Gravitational Wave Observatory), and its European counterpart VIRGO (Ref. [6], p. 915). The success of these instruments depends directly on the laser power that can be employed. The computer modelling and simulation techniques mentioned above are also directly applicable to problems in general relativity, black holes and cosmology.

Both the above areas of focus, i.e. laser technology, and atmospheric and space science (including general relativity and gravity), require that related areas of strength in Canada be maintained concerning the acquisition of basic atomic and molecular data needed as input and for the interpretation of results. These particularly include:

- Optical spectroscopy of all forms from the microwave to the far ultraviolet.
- Electron and atomic collision studies involving interactions in both the gaseous and solid phases.

The following section outlines a proposal for a new initiative in laser science and spectroscopy to capitalize on Canadian strengths in these areas.

11.1 Laser Science and Spectroscopy Initiative

During the early experimental work that precedes the development of every successful technology, a period is reached when it becomes possible to predict, on the basis of emerging experimental evidence, a realistic vision of the role that technology will eventually play in society. Decades ago, scientists doing early work on lasers were able to foresee applications that must have seemed like pipe dreams to others: that one day telephone messages would travel on laser light, that musical notes would be recalled from storage using laser beams, and that surgeons would operate with scalpels of light.

The field of laser science and spectroscopy research has now reached the stage where the broader horizon of possibilities has come into view. It is possible to foresee the day when intense lasers are so well engineered that they can be used in dentist offices. We can foresee the day in which short pulse lasers will have become so simple technically that they will be used routinely in production lines or hospitals. Investing in spectroscopy and laser science is an investment in the future is that is guaranteed to pay off.

11.1.1 History of Spin-Offs

Spectroscopy—the means that science uses to communicate with atoms, molecules or solids—has led to many very important scientific advances that affect all of our lives. It was the study of spectroscopy that led to quantum mechanics and revolutionalized our understanding of biology, chemistry, and physics. Spectroscopy also led to the laser, perhaps the most important scientific advance of the past 50 years. Now lasers have in turn become a powerful tool for many new approaches to spectroscopy.

While spectroscopy continues to spin off new subdisciplines such as pollution monitoring and medical diagnostics, laser science, one of spectroscopy's progeny, has penetrated almost every area of science and technology. For example, we now trap and manipulate biological organelles within cells with laser beams. We also trap atoms in laser beams. Laser discs are read, medical operations are performed and fusion is triggered with laser light.

Not only is spectroscopy spinning off new subdisciplines, but it is modifying already established areas. Many aspects of atomic, molecular, plasma and solid state physics are merging into an intellectual whole because of the ubiquitous nature of laser science and spectroscopy.

11.1.2 New Scientific Directions

The creativity of spectroscopy and laser science shows no signs of waning. Five characteristics of laser pulses are leading to new scientific directions:

1. Duration: Laser pulses now dominate all fast measurements. Electronics has long since been left behind. Modern laser pulses are short enough (about 4.5 fs) to follow the path of almost any chemical reaction and many fast process important in biology and physics. It appears that even shorter pulses (about 100 attoseconds) will be generated within the next few years, opening the door to studying even faster processes. Learning to exploit these new tools is an important and exciting challenge that is sure to lead to new understanding of matter and the dynamic processes that matter undergoes.

2. Phase: Phase entered mechanics as a variable for the first time with quantum mechanics. However, during the first 60 years of quantum mechanics, we have observed the consequences of phase, but phase was not exploited as a control variable. The ability to control and manipulate the phase of matter through the manipulation of the phase of light is just beginning to change

that. It is now feasible to excite many physical and chemical processes using two or more different pathways and control the process through the relative phase of the laser beams. It is as though we "construct" a matter interferometer using light, and control chemical or physical processes through quantum mechanical interference between alternative pathways to the same final state.

As some examples, by changing the phase between fundamental and second harmonic light, the following effects have recently been demonstrated. (1) The direction of emission of electrons produced by photoionization of atoms or small molecules can be controlled. (2) The magnitude and direction of photocurrents in semiconductor devices can be varied. (3) The direction of fields inside optical fibres leading to second harmonic generation can be controlled. In addition, theoretical calculations by Brumer and Shapiro [Scientific American **272**, 56 (1995)] show that the branching ratios between photochemical pathways in molecular photodissociation can be controlled. This field is now often called *coherent control*. Phase is an almost unexplored control variable that quantum mechanics makes available, and the potential for future development is enormous. It will be the task of physicists and chemists to determine the scientific and engineering opportunities that phase control gives. It is almost impossible to imagine that the exploitation of such a fundamental variable will not lead to important new technologies.

3. Intensity: Laser pulses have given experimentalists access to intensities that were previously unimagined. The early development of what has become known as nonlinear optics led to both a Nobel prize and to a rapidly expanding industry which promises such science fiction-like devices as optical computers. During the past five years there has been a major increase in the intensity that lasers can produce. With the chirped pulse amplification technique, intensities produced by even modest lasers can now easily reach the level where electrons exposed to laser light oscillate in the electromagnetic wave with relativistic velocities. Thus relativistic physics can be brought to the bench top for the first time and it can be exploited in technological applications. One major advance that is sure to follow high intensity laser pulses is new ways of making very short wavelength (x-ray) radiation. We can foresee the day when even dentists offices have intense laser sources.

   The very short durations of ultrafast laser pulses enables atomic, molecular and solid state materials to withstand very high intensities without damage. These laser pulses can apply forces that are strong enough to compete with the forces binding the electrons to an atom or the atoms in a molecule or solid. These are tools powerful enough to control fundamental processes. Understanding and exploiting this new tool is a clear scientific frontier with important technological implications.

4. Bandwidth: There is a symbiosis between the rapid advance of narrow linewidth lasers and the rapid advance of spectroscopic techniques, often based on lasers, that allow us to measure very precisely. With ever more precise measurements, it will be possible to test basic theories to the limits of their validity. High precision measurements are already making important contributions to areas such as parity violation that were previously the exclusive realm of particle physics.

5. Wavelength: Historically, the technology of laser physics has continually expanded its horizons to shorter or longer wavelengths, to higher intensities, and to shorter pulse durations. These relentless advances continue, and one of the new forefronts will be in the x-ray spectral region. It is high intensity lasers that will lead us there. The development of high quality, intense, ultrashort-pulse and convenient x-ray sources is the current frontier and will remain so for the next decade. These new sources will complement synchrotron light sources (such as the proposed Canadian Light Source in Saskatchewan) in that the laser sources will have much shorter pulse

durations and much higher peak powers, but perhaps lower average powers. From this research, not only will a new source emerge, but also new areas of x-ray nonlinear optics and x-ray holography.

11.1.3 Future Research Programs

The above new scientific directions lead naturally to two programs that are built around Canada's historic strength in spectroscopy and related atomic and molecular interactions. The first should be aimed at expanding the physics of spectroscopy and laser science itself. The second should exploit the multidisciplinary nature of spectroscopy and laser science by applications to other areas.

Physics of Spectroscopy and Laser Science. Spectroscopy and laser science are one of the most promising fields of study in physics. It is a field that is expanding rapidly both in its scientific opportunities and in its industrial applications. There are many employment opportunities for students in the field.

The scientific problems that can be addressed in spectroscopy and laser science are both fundamental and original. These include (1) time resolution of any process that involves motion of atoms in molecules and solids (this includes all of chemistry), (2) extreme nonlinear optics, (3) x-ray generation and applications, (4) strong field physics of atoms or molecules, and (5) control and applications of quantum interference. The historic close interactions between technology and science mean that the prospects for engineering spin-offs are great. The strong Canadian laser industry is testimony to a history of spin-offs.

Advances in laser technology would benefit from and be assisted by other existing Canadian programs in basic atomic and molecular physics such as spectroscopy, electron-atom scattering, atom-atom interactions, collision-induced absorption (CIA), molecular beam techniques, and theoretical programs relating to all of these.

Physics of Atomic and Molecular Interactions. Figure 1 (p. 3) illustrates many of the linkages between the different areas represented in this report. The point has been made that AMO science is both a basic and enabling science. Thus fresh initiatives in this area should be encouraged both to produce exciting new discoveries and to provide other branches of science and industry with the data base which they need.

Studies of atoms, molecules, ions and clusters, including their structure and properties, optical interactions, collisions, and interactions with electrons, external fields and solids and surfaces should be encouraged as an essential adjunct to the laser physics initiative. Of particular interest are the control and manipulation of atoms, molecules and charged particles. For example, the properties of Bose-Einstein condensates and their potential for creating atom lasers are just now unfolding as a powerful new technique for the control and manipulation of atoms. The implications for both fundamental science and technological applications may well be as profound as the invention of the laser itself.

Multidisciplinary Topics of National Concern. Spectroscopy and laser science are multidisciplinary by nature, influencing not only physics, but also chemistry and biology. The concepts developed in one discipline are frequently transferred to others. Some examples are:

1. **Manipulation of Biological Organelles.** Laser trapping is one of the most dramatic advances in atomic physics. It developed from research on laser trapping of mesoscopic materials.

Trapping and manipulation of biological organelles (optical tweesers) is just becoming a commercial technology in biological science, allowing individual parts of a cell to be moved around and examined at will. The possibilities for new techniques and insights into the workings of living cells are endless. A similar force that promises laser trapping of molecules has just been demonstrated.

2. **Opto-electronics Industry.** The use of lasers to control currents in semiconductors (opto-electronics) is a rapidly expanding field. The aim is to develop a whole new class of electronic devices which are limited in their characteristics only by the intrinsic properties of materials, and not by external capacitances, inductances etc. Eventually, microlasers will be integrated with other electronic components onto a single chip.
3. **Pollution Monitoring.** Lasers and spectroscopic techniques such as lidar are ideally suited to pollution monitoring where it is necessary to make measurements at a distance. Similarly, spectroscopy is the basis of many astronomical measurements.
4. **The Controlled Fusion Program.** Advances in laser technology would have immediate application to plasma physics and the controlled fusion program, both as a plasma source and a plasma diagnostic. This is an area where Canada can continue to contribute to the international effort, even if the controlled fusion program *per se* is phased out in Canada.
5. **Medical Applications.** Medicine is an area where spectroscopic techniques are being developed to diagnose and treat diseases such as cancer. For example, sub-picosecond laser pulses allow one to produce extremely small-size plasmas which act as point sources of hard x-rays. The Kieffer team at INRS has developed a research program to assess a laser-based hard x-ray source for medical imaging. This work is in collaboration with the SUNY Health Science Center at Syracuse and is supported by the NIH (U.S.).

In addition to the above, the new multidisciplinary areas of spectroscopic research include:

1. application of laser x-ray sources to studies of atoms, molecules, or biological samples. A particularly important objective to reach is the so-called "water window" between wavelengths of 20 and 40 nm where water becomes transparent in the x-ray region. This would allow the *in vivo* study of biological samples without special preparation of the sample.
2. use of coherently related pulses to control the outcome of chemical reactions and material processes.
3. application of femtosecond techniques to create "snap-shots" of rapid processes in atomic, molecular, solid state or biological systems.

As NSERC considers the opportunities, it should keep in mind the synergy between advances in laser science and the major Canadian thrust in opto-electronics. Canada is one of the world's major scientific powers in optical science and engineering. This expertise is broadly based in industry, government and universities, and it involves strong collaborative interactions with condensed matter physics. By expanding optical science, NSERC has an opportunity to influence Canada's high-tech future.

11.1.4 Existing and Planned Ultrafast Laser Facilities

Since 1990, the number of Canadian researchers involved in the field of Ultrafast Laser Matter Interaction (ULMI) has steadily increased. Canadian research in this field now links over thirty researchers in seven universities (University of British Columbia, University of Alberta, University of Toronto, INRS at Université du Quebec, Université Laval, Université de Sherbrooke, University of Waterloo, and McMaster University), in Government Laboratories (Steacie Institute for Molecular Sciences at the NRC) and in industrial research laboratories (IREQ).

Several laser facilities have already been developed or are currently under development. The principal ones are:

1. University of Alberta: a 0.5 TW, subpicosecond KrF laser system (400 fs, 0.25 μm wavelength, low energy) is being used to explore the physics of nonequilibrium processes in optically ionized gases and short wavelength sources.
2. University of Toronto: a 1 TW all Nd glass CPA laser system (1 picosecond, 1.05 μm wavelength, 1 Joule) is being used to study harmonics from solids and vuv laser physics.
3. INRS: a 2 TW, subpicosecond hybrid Ti:sapphire–Nd glass laser system (80 - 400 fs, 1.05 μm wavelength, 1 Joule) is used at INRS to study hot solid density plasma physics, high-field laser-matter interactions (10^{20} W/cm^2), and ultrafast x-ray sources. Assessments of these ultrafast keV x-ray sources for medical imaging and chemical reaction probing is under way.
4. HYDRO-QUEBEC research institute (IREQ): a 10 Hz, 2 TW (100 fs, 200 mJ) laser system is under development at IREQ and will be specifically dedicated to studies of laser-induced lightning.
5. Université Laval: a 2 TW, Ti:sapphire laser system (100 fs, 0.8 μm wavelength, 200 mJ) is used to explore the physics of laser interactions with gas targets (ionization, harmonic production).
6. University of Waterloo: A high repetition rate sub-hundred femtosecond laser will be constructed to investigate laser interactions with molecules and their coherent control.

In summary, a strong initiative into the development of laser science and technology holds excellent promise for future scientific pay-offs, and it would contribute greatly the diversity and vitality of many other areas of physics and interdisciplinary studies.

11.2 The Canadian Light Source (CLS) Proposal

A proposal has recently been submitted to NSERC by the Canadian Institute for Synchrotron Radiation for the construction of a national synchrotron light facility in conjunction with the Saskatchewan Accelerator Laboratory. Worldwide, 10 to 15% of total synchrotron radiation (SR) use is for research in atomic and molecular science. One could expect a similar level of usage of the proposed CLS in Canada. The unique advantages of high intensity and tunability are useful in studies such as photoabsorption, photoionization, photodissociation of molecules, and fluorescence techniques for the study of molecular dynamics. The existing Canadian access to a beam line on the Alladin synchrotron facility in Wisconsin is a poor substitute for a Canadian national facility. Canada is the only G7 country without a synchrotron light source, and the exponential growth of SR usage elsewhere indicates that the need for a Canadian facility will be critical by the year 2000. The wide range of scientific and industrial applications of SR is fully documented in the CLS proposal.

The laser science and spectroscopy initiative proposed here would complement the CLS in two ways. First, existing laser sources, or those soon to be developed, can be combined to advantage with SR in experiments where, say, a laser photon is used to produce a transient species that is subsequently studied with SR, or vice versa. Second, the future development of x-ray lasers would augment the capabilities of SR by producing shorter pulses of higher peak powers, but perhaps of lower average power. Also, x-ray lasers would have coherence characteristics and phase control not possessed by SR. Ultimately, x-ray lasers may complement some of the current uses of SR for precise chemical analysis and the characterization of materials. The proposed CLS would lend access to Canadian scientists to rapidly evolving research areas directed at the understanding of many-electron phemonena in atomic inner-shell dynamics, fundamental photon-atom and molecule interactions, as well as relativistic and quantum electrodynamic phenomena.

11.3 Mathematical Physics

The greatest concentration of mathematical physics, as defined and funded by GSC-29, is in the Montréal area and is concentrated around the CRM (see Sect. 8.3, p. 55). One of its strengths is its interdisciplinarity, with strong ties to pure mathematics on the one hand, and to experimental physics and applied sciences on the other. This orientation should be maintained and further encouraged. The important role of theory as a unifying element in physics is fully discussed in Sect. 8 (p. 53), and mathematical physics lies at its foundations.

11.4 General Relativity and Gravity Research

There are three prime areas of Canadian strength in general relativity and gravity. The first of these is in the links with observational physics, whether through the observation of gravity waves, or through astrophysics and cosmology. The coming on-line of gravity wave detectors around the world in the next ten years is an opportunity which Canada must grasp. Because of Canada's strength in theory, this will in the first instance be theoretical. The number working on gravity wave detection is at present small, with perhaps two active researchers in area. Thus our strength in this area will depend on university hirings over the next few years. However the combination of difficult analytic challenges together with forefront numerical problems make this a field of immense promise.

The second area of emphasis is in the links between particle physics and gravity. As mentioned at the beginning of Sect. 7 (p. 41), understanding gravity in the context of particle physics is one of the top priorities in the field world wide. While string theory, for example, has been beset with almost intractable difficulties in being crafted into a calculable theory, its advances have been surprising and steady. It is thus uncomfortable that Canada again is weak in this area, with perhaps two researchers across the country engaged.

Although string theory *per se* is under-represented, there is a growing emphasis in Canada on alternative approaches to the quantization of the gravitational field (i.e. quantum gravity). This is an area of current strength in the country, with people at Alberta, British Columbia and Waterloo, and it is one for which the future holds hopes of significant advances. As both allies and critics of the particle physics approaches to the area, the researchers here form a nucleus from which Canada's strength in the next century can grow.

A third area of potential growth is in numerical general relativity. Because of the challenges that the theory offers to traditional mathematical techniques, many of the key advances in our knowledge of how highly relativistic systems behave gravitationally will come from numerical studies. This is again a field in which the solutions challenge the state of the art in numerical computer science, and offer the probability of significant advances in the next ten years. As an example, the NSF has funded a Grand Challenge in Numerical Relativity in the U.S. This area presents the possibility of linking Canada's present expertise in general relativity to its strength in computer science, and even in computational fluid mechanics.

Unfortunately, the area in which Canada has had its traditional strength, namely mathematical relativity, is also one in which the major advances have been relatively few. Although the classical theory still offers great challenges, these do not appear at present to be central to the development of the field in its impact on physics. The one area in which this is not true is in the development of approximation schemes for the theory as applied to astrophysical situations. It is embarrassing that after 80 years, we are still a long way from understanding in detail the "two body" problem in general relativity, and current approximation techniques appear to be inadequate to predicting the emission of gravitational radiation from such a binary system. Although Canada has only one young faculty member (E. Poisson) working in this area, it is and area which promises to repay any investment made in it by research advances, especially because of its links to the experiments around the world, and to the numerical effort mentioned in the preceding paragraph.

Finally, the community must seek more ways of increasing the contacts between the researchers across the country. Isolation can be very detrimental to the maintenance of a vibrant career. The one mechanism in place at present, namely the biennial Canadian Conference in General Relativity, does serve this role, but only to a very limited extent. This conference presents a unique opportunity for bringing together the researchers to talk to each other and to talk with distinguished invited speakers from around the world. It thus represents an opportunity for the rejuvenation of the field. However it cannot do so on its own, and the community must come up with other techniques as well.

11.4.1 Relation of Theory and Experiment

By and large, the Canadian physics community has a reasonable balance between theory and experiment. However, general relativity is anomalous in that it is an almost exclusively theoretical field of research. As a general rule, a predominance of either experimental or theoretical physics in any area weakens that area. It is therefore gratifying that many of the young researchers in the area of gravity have strong links to experiment, whether to astrophysics and cosmology, or to gravitational experiments (e.g., gravity waves).

However, despite the dominance of theory in the field at present, we feel that this is still the area of gravity research in which Canada can have its largest impact. Theorists are relatively cheap, not necessarily to hire, but certainly to fund their research. Their equipment costs are small (and even computers for numerical experiments are in the low end of equipment costs), and they have the ability to create links with the best researchers in the world in way that experimentalists tied to their equipment often find difficult. As the example set by the CIAR in Alberta, UBC and Toronto shows in this area, theorists can have an impact on the field very rapidly, and can put Canadian research on the map in a very short period of time.

12 Distribution of NSERC Funds

The foregoing sections have outlined the various research programs funded by GSCs 17 and 29, and their prospects for future development. In this and the following several sections, we turn to the other items listed in Sect. 1.2 (p. 4) relating to NSERC funding policies and criteria, based on responses to the questionnaire reproduced in Appendix E. Those not familiar with the NSERC granting system should also refer to Appendix A.

One of the questions posed in the charge to the Committee was to determine how funding should be distributed to attain the appropriate level of research diversity, focus and risk-taking for future programs. Several questions in Section IV of the questionnaire addressed this issue with the following results.

12.1 Selectivity

In order to accomplish best the objectives for physics research in Canada within the available funding, respondents were asked to choose whether the GSCs should be (1) more selective, (2) about the same, or (3) less selective, and to give the rationale for the choice (Question IV.1). The results shown in Table 7 show that most people who answered are satisfied with the current degree of selectivity. However, a substantial number (22 out of 69) did not answer, or gave a rationale indicating that there is no simple answer. Comments indicated that many people feel frustrated with the current levels of funding, and are torn between the need to support good work at internationally competitive levels through greater selectivity, and the need to maintain a broad research base in all universities with emphasis on the training of students at both the undergraduate and graduate levels. The kind of science supported by GSC-29 is supremely well suited to the training of students, but many people feel that funding levels are already at or below the critical level to accomplish both objectives.

Figure 2 shows the distribution of operating grants for GSC-29 over the past seven years (1990–1996), and Fig. 3 shows the 1996 distribution in greater detail. Figures 4 and 5 show the corresponding distributions for GSC-17. The GSC-29 distribution clearly shows a persistent double peak with one peak around \$15k and one peak around \$25k. The GSC-17 distribution has a relatively larger number of small grants with a second peak around \$50k. These distributions undoubtedly result from the attempts of the GSC's to support a few individuals with large grants, while at the same time maintaining a larger base of researchers with minimal levels of support.

12.1.1 Selectivity in General Relativity and Gravitation

Figure 6 shows a histogram of the grant sizes for those individuals listed in Table 2 (p. 45) who have an NSERC grant. (Note that the others do not have grants for a variety of reasons, including

Table 7: Questionnaire responses on GSC selectivity. Do you think that the Physics GSC's should be:

Choice	Number
more selective	12
about the same	31
less selective	4
no answer	20

Figure 2: Distribution of operating grants for GSC-29 over the past seven years.

Figure 3: Distribution of operating grants for GSC-29 for 1996.

Figure 4: Distribution of operating grants for GSC-17 over the past seven years.

Figure 5: Distribution of operating grants for GSC-17 for 1996.

Figure 6: Distribution of 1995–96 operating grants for the general relativity and gravity researchers listed in Table 2.

retirement). These figures are for the 1995-96 NSERC fiscal year. As can be seen from this, the grants vary tremendously from ones near the largest of any NSERC researcher in any field, to others significantly below the median grants in their GSC.

It is clear from the histogram that there is little "fat" left in the system; i.e. the grants have been distributed in a highly selective fashion. In the Space and Astronomy GSC-17, the median grant is about \$24K and the average about \$30K. However, the average of the general relativity and gravity (GRG) community funded by GSC-17 is about \$35K. Many of the lower grants are funded from other GSCs, such as Mathematics, where the mean grants are much much lower (of the order of \$12K). (The average grant of the nine GRG researchers in Table 2 who are funded by the Mathematics GSC is approximately \$9K.)

12.2 Regional and Geographical Distribution

Respondents were asked whether there are special considerations that should be taken into account regarding regional and geographical distribution of grants [Question IV.2(a)]. As with the preceding question of selectivity, the results in Table 8 show that there is a strong dichotomy in the perceived purpose of NSERC grants between the support of research *per se*, and the role of research in the education of students at both the graduate and undergraduate levels. Of those who responded, the majority (24 out of 44) answered "no" on the grounds that the quality and merit of the proposal alone should be the only criteria. Those who answered "yes" did so on the grounds that (1) it is important to maintain a broad base of university research activity in all regions, (2) there are special regional considerations in areas such as oceanography or atmospheric/space science, or (3) there is a need for balance with respect to large blocks such as the Maritimes, Québec, Ontario, and

Table 8: Questionnaire responses on regional and geographical distribution of grants. Are there special considerations that should be taken into account?

Response	Number
yes	15
equivocal	5
no	24
no response	25

Table 9: Questionnaire responses on support of research in smaller universities. Are there special considerations that should be taken into account?

Response	Number
yes	24
equivocal	2
no	20
no response	23

western universities. On balance, quality and merit should be the principal criteria, but regional and geographical issues should be taken into account if there is a specific justification for them, or if there is a pronounced imbalance in the distribution across broad regions of Canada.

12.3 Support of Researchers in Smaller Universities

Respondents were asked whether there are special considerations that should be taken into account regarding the support of researchers in smaller universities [Question IV.2(b)]. The results in Table 9 show that there is relatively stronger support for this concept. The majority of those who responded (24 out of 46) answered "yes" on the grounds that either (1) good research should be supported wherever it is found, but the needs are greater in smaller universities due to lower levels of infrastructure support (technicians, university contributions to funding, heavier teaching loads, etc.), and/or (2) it is necessary to support research in all universities since it is an essential component of good teaching at both the undergraduate and graduate levels. Those who answered "no" (20 out of 46) argued that quality and significance should be the only criteria in times when levels of funding are under severe pressure. We must identify those things that we do best and fund them well. On balance, quality and significance should remain the principal criteria, but a broad base of research diversity and educational quality is best maintained if the special needs for support in smaller universities is also taken into account. This would help to avoid the emergence of a two-tier university system consisting of research "haves" and "have-nots", and their consequent differences in quality.

A similar policy has been adopted in the U.S. where the National Science Foundation has specific programs to support research in purely undergraduate institutions. The American Physical Society also clearly recognizes the importance of educational outreach. The role of research in education is further discussed in Sect. 22 (p. 113).

Table 10: Questionnaire responses on risk-taking and diversity in research. Are there special considerations that should be taken into account?

Response	Number
special considerations are needed	21
system is adequate as it is	9
no response	39

12.4 Support of Risk-taking and Diversity in Research

Respondents were asked whether there are special considerations that should be taken into account regarding the support of risk-taking and diversity in research [Question IV.2(c)]. The responses were classified as shown in Table 10, although the two categories indicated are not mutually exclusive in that the need for special considerations does not necessarily imply that the present system is inadequate. Those who answered "yes" (21 out of 30 who responded) primarily addressed the question of risk-taking, i.e. the support of proposals of a more speculative nature. The primary concern was to caution that the proposal should be discussed in terms of the scientific excellence of both the researcher and the proposal, together with potential commercial benefits if applicable. One respondent suggested that 5% of the GSC budget might be allocated for risky projects up to a maximum of $20,000 per grant, and that progress be carefully monitored.

Many of those who thought that the system is adequate as it is questioned the assumptions underlying the concept of risk-taking in research as a separate criterion. Different research projects have different probabilities of yielding useful results. As a general rule, supervisors assign projects to graduate students when they feel reasonably confident that useful results will emerge, while leaving research of a more exploratory nature (whether fundamental or applied) to themselves, or to more advanced research associates or postdoctoral fellows. A vigorous research program should contain a balance of both components. Even the most routine work often yields surprises. To paraphrase Feynman, things are always more complicated than they seem at first. Some of the specific points raised along these lines are:

- All research is "risky" in that the outcome is not predictable. Otherwise it is not research.
- In effect, risk-taking is already supported by giving longer-term grants to established researchers, thereby enabling them to undertake longer term projects of a more exploratory nature. It is the new researcher who needs quick and sure results. Excellence should be paramount, and one must distinguish between "risks" and "gambles".
- NSERC should support the best people, and the risks and diversity will follow. NSERC is the only real source of money in Canada that is not targeted, and this feature alone allows both risk-taking and diversity to take place.
- More risk-taking would accompany better funding.

In summary, respondents felt that risk-taking and diversity are factors that should be taken into account by GSC's, but not necessarily more so than is currently the case. Quality and excellence should be paramount. Any vigorous research program should contain a balance between projects likely to yield useful results in the short term, and those of a more exploratory nature where the outcome is less certain.

Table 11: Questionnaire responses on minimum useful grant sizes.

Amount of grant	Experiment	Theory
no minimum amount	8	10
\$1 000 – 2 000	2	2
\$3 000 – 5 000	4	8
\$10 000	10	12
\$20 000	12	8
\$30 000	2	1
\$40 000	1	0
depends on field	4	3
no response	23	23

Table 12: Questionnaire responses on maximum funding levels.

Amount of grant	Number
no maximum amount	19
\$50 000	6
\$75 000	2
\$100 000	2
\$150 000	1
\$200 000	1
depends on field	5
no response	33

12.5 Minimum Useful Grant size

Respondents were asked whether they believed in the concept of a minimum useful grant, and if so what level(s) would be appropriate (Question IV.3). The 46 responses were divided into ranges as shown in Table 11. Some respondents specified different amounts for experiment and theory respectively. Those who did not specify were assigned to both categories, and this accounts for most of the minimum amounts in the lower range for experimentalists.

The results indicate that the minimum useful grant for experimentalists is normally around \$20,000, although smaller grants should not be automatically excluded in exceptional cases if properly justified. For theorists, the minimum useful amount is probably closer to \$10,000, although here a stronger case can be made for the continued support of theorists in cases where the productivity is low, but of high quality and significance. Some allowance for grants in the lower range is important for the maintenance of diversity in research, and the preservation of a broad research base for the education of students. It does not follow from the need for selectivity that those at the lower end of grants should be automatically cut off if the work is of high quality, though perhaps low in volume, and the needs of the researcher are being adequately met. Several respondents commented that the minimum amount should be enough to support a graduate student, pay publication costs, and attend a conference.

12.6 Maximum Funding Levels

Respondents were asked whether they believed that there should be some maximum funding level(s) for an individual, and if so what should it(they) be (Question IV.4). The 36 responses were divided into ranges as shown in Table 12. In this case, most respondents did not distinguish between theory and experiment, and so no separate figures are given. However, it must be recognized that, generally speaking, grants at the upper end are higher for experimentalists than for theorists because of the extra costs associated with running a laboratory.

Unlike the case of minimum grant sizes, the majority of respondents (19 out of 36) did not favour having an upper limit on grant sizes, or at least not making a public proclamation about it. The main criterion should be the ability to make good use of the funding. However, some cautionary notes were expressed that the good done by a single large grant should be carefully weighed against support for collaborative facilities, or support for additional researchers if the large grant were slightly reduced.

12.7 Comments on Startup Grants

Respondents were asked whether they had comments on the present situation regarding startup grants for new researchers (Question IV.5). Given the current tightness of funding, most felt that there was little room for expansion at the expense of established researchers. However, several people suggested that there should be greater encouragement for partnerships between NSERC and the universities to provide appropriate levels of funding for the establishment of new laboratories.

12.8 Comments on Equipment Grants

Respondents were asked whether they had comments on the NSERC equipment and major equipment funding programs (Question IV.6). Virtually all experimentalists and many theorists pointed out the urgent need to replace obsolete or worn out equipment, and complained that the success rate for equipment grant applications is too low. There is an overall lack of infrastructure support for equipment, especially now that infrastructure grants have been phased out. In addition, equipment grant applications for computers are putting a further strain on funds available for more traditional types of equipment.

One respondent noted in particular the time delays associated with equipment grant applications, which puts him/her at a competitive disadvantage relative to colleagues elsewhere in the world, and suggested an "open date" policy for equipment grant applications with no submission deadline.

13 Participation in Collaborative Projects

In order to gather general information on the degree to which the respondents were participating in collaborative projects, they were asked whether they were involved in collaborative projects, and if so to classify them under (a) university-based collaborations, including those with other disciplines, (b) industrial collaborations, and (c) other collaborations, such as with government laboratories. Of the 69 responses, 56 (or 81%) reported that they were involved in collaborative projects of one sort or another. Many reported multiple collaborations. The various types of collaborations are summarized in Table 13.

Two things are particularly noteworthy from Table 13. First, nearly 60% reported collaborations with colleagues in other universities, and of the 66 collaborations mentioned, 83% were with universities outside of Canada, primarily in Europe, Japan and the United States. This indicates the high degree of influence that Canadian physics research has on other scientists around the world. Second, nearly 1/3 of the respondents reported collaborations with industry, and also 1/3 with other disciplines. The specific industries and disciplines mentioned are listed in Tables 14 and 15. Both these lists are certainly only a partial representation of the total activities in the community.

The other side of the coin is the range of disciplines which the respondents draw upon in the course of their work (Question II.13). Twenty-seven respondents answered this question, with the results shown in Table 16. The most frequently mentioned discipline is chemistry (including biochemistry), with polymer chemistry and methods for the characterization of surfaces playing the most important role. The frequent mention of lasers and optical science as a tool in other areas of research is also prominent. In fact lasers and optical science, together with materials science, form the single largest block.

13.1 Collaborative Studies in Atmospheric/Space Science

Since collaborative studies in atmospheric physics and space science have special characteristics, they are separated out for special treatment in this section. As can be seen from Table 17 there is, at least among the respondents, a significant degree of collaboration. Eight of twelve are involved with industry and nine of twelve with other Institutions. These numbers may seem significantly higher than for other branches of physics, but this probably arises from the association of most of the respondents with CSA projects, which necessarily involve an industrial component. Proposals for new projects supported by the CSA, through their "Announcements of Opportunity", require a formal industrial partnership and so are fostering (forcing) this collaboration. The size of these projects also encourages collaboration with other agencies/universities as the highly qualified personnel requirements are usually beyond the resources of one institution.

Table 13: Questionnaire responses on collaborative research projects.

Type of collaboration	No. of responses	No. of collaborations
Same discipline, other universities	41	66
Other disciplines	22	28
Industry	21	28
Other agencies	15	20

Table 14: Companies named as industrial collaborators.

Company name	Company name
Alcan	N.B. Telephone
Allatel-Constar	Noranda
Allied Signal	Nortel
Alterra Laser Technologies	Ontario Hydro
Armstrong Corp.	Optech
Chrysler Canada	QPS Technologies
General Motors (U.S.)	Resobrees Canada
General Systems Research	Resonance Ltd.
Hydro-Québec	Sciex
Imperial Oil	SDL Optics
Lockheed Martin Electronic Systems Canada	Surface Canada
MPB Technologies	

Table 15: Disciplines named as interdisciplinary collaborators, and the number of occurrences of each.

Discipline	No.	Discipline	No.
Archeology	1	Home Economics	1
Biology	3	Materials Engineering	1
Chemistry	6	Mathematics	4
Civil Engineering	1	Mechanical Engineering	1
Electrical Engineering	3	Medicine	1
Geology	1	Nuclear Physics	1

Table 16: Other (sub)disciplines drawn upon in physics research.

Discipline	No.	Discipline	No.
Astrophysics, cosmology	3	Lasers and optical science	6
Chemical engineering	1	Materials science	4
Chemistry and biochemistry	9	Mathematics	5
Civil engineering	1	Nuclear radiation	1
Computer science	4	Nutrition chemistry	1
Electrical engineering	3	Plasma physics	1
Environmental science	2	Spectroscopy	2
Fluid dynamics	1	Zoology	1

Table 17: Summary of collaborations in atmospheric/space science with industry and other agencies/universities.

Item	Industry	Other Agencies/Universities
1	Optech (spin-off company), laser technology development.	ISTS, NASA etc. laser applications in atmospheric remote sensing.
2	Off-shore as Canadian prices too high.	McGill and Cornell development of radar at geomagnetic pole.
3	Bristol rocket experiments.	UNB detector development.
4		SuperDARN international network.
5	Bristol rocket experiments, Routes and Sci-Tec satellite instrumentation.	Trent, York, Johns Hopkins and Stockholm, modelling and satellite date retrieval.
6		Other universities involved in atmospheric dynamics.
7	Bristol rocket experiments, Routes satellite instrumentation.	AES, Trent, Sask., Michigan and Stockholm, modelling and satellite data retrieval.
8	Instrumentation and analysis for resonance gas detection.	Trent and Harvard spectral analysis.
9	Sci-Tec satellite instrumentation	
10	Com-Dev and SED for space instrumentation development	Japan and other institutes for space instrument analysis.

14 Encouragement of Research Partnerships with Industry

Given the growing emphasis on research partnerships, particularly with industry, respondents were asked if there were ways that researchers could be helped in their participation, particularly those in less industrially developed parts of Canada (Question IV.7). Of those who addressed this question, nearly half (12 out of 25) expressed concern that sufficient funds were already being directed toward research partnerships with industry through existing granting mechanisms, research institutes, and networks of excellence. As indicated in Sect. 13 (p. 93), about 1/3 of the respondents have already established various types of industrial collaborations. They questioned whether it is the proper role for NSERC to provide further support for industrially related research. They argued that existing scientific and economic forces were sufficient to bring about collaborations if they were really justified, and geographic location is becoming less important as communication networks improve. These comments were not meant to question the role and value of research partnerships with industry, but to argue that existing mechanisms are already sufficient.

There is a danger that NSERC programs to encourage research partnerships with industry will just amount to a subsidy for research that should be funded by industry in the first place. It relieves industry of the need to maintain their own research facilities if the work can be transferred to universities. There are two problems with this transfer. First, it shifts the focus of university-based research from fundamental studies and the advancement of knowledge to short-term applied problems of direct interest to industry. While applied research is not out of place in universities, their unique role in society is for the advancement of knowledge and its dissemination through teaching. Second, the transfer eliminates research careers for physicists in industrial laboratories.

Those who had specific comments on how to encourage research partnerships pointed out that they felt at a loss as to how to go about setting one up and suggested that the shared experiences from others would be useful. Different fields need different approaches. Some specific suggestions are:

- Hold a workshop at the next CAP Annual Congress on research partnerships and how to establish them. A CAP Organized Retreat on Industry-University Cooperative Programs is now planned for the 1997 Calgary meeting.
- Part of the mandate for NRC is to help industry. Perhaps NRC should be more aggressive in acting as the link between industry and the universities.
- Establish an NRC or NSERC web server to provide match-making services.
- Small high-tech industries are often more amenable to partnerships than large ones, and they are more likely to profit, but are less likely to have disposable cash. Perhaps a graded level of industrial contribution dependent on size would be beneficial.
- More remote researchers should join with more centrally located ones who have already established industrial contacts. The result would be a stronger team that looks better to the industrial partner.
- While geographical proximity makes things easier, it is by no means necessary. Communications are easy (via videoconferencing etc.), and travel is a valid expense.

14.1 Role of Students in Technological Transfer

One of the most effective ways of facilitating the transfer of technology from universities to industry is through the students who carry it there. This is a long-standing form of "research partnership", although it is not officially formalized as such. In Question VI.6, respondents were asked if they

Table 18: Questionnaire responses on the transfer of technology to industry by graduate students.

Industry	Type of transfer
Canstar II	fibre optics for telecommunications
InSpeck	holographic techniques
CAE Montréal	holographic techniques
Cie Optiwave Corp.	fibre optics
Advanced Laser and Fusion Tech.	plasma modelling
Nortel	opto-electronics
Dalsa Inc.	opto-electronics
Lumonics	laser technology
JK Lasers	laser technology
Hughes (U.S.)	plasma generated radiation sources
Borealis Lasers	plasma discharges for laser media
Societé Anonyme de Telecommunications (France)	laser technology for lidar
Vortek	plasma arc technology
Optech	laser technology for lidar
Barringer Research	ion-mobility trace gas detector

could cite examples of graduate students carrying technological skills or innovations from their research into industry. Of the nineteen responses, many cited the transfer of general research skills such as programming, high vacuum technology, or electronics to a variety of companies. The more specific cases of technology transfer are summarized in Table 18. In addition, several other graduates have formed their own high-tech companies. For example, Bomem Inc., Exfo Inc., Nortech Fibronics, and Surface Canada are all multinational Corporations founded by ex-Laval students or postdoctoral fellows. Another example is Resonance Ltd. (Barrie Ontario) founded by W. H. Morrow, a graduate of York University who turned the techniques he developed there for remote atmospheric sensing into a successful space instrumentation company.

Question VI.4 asked for ways in which technological transfer by students from universities might be improved. Of the 17 respondents who answered this question, most either indicated that a graduate co-op program already existed at their university, or suggested that one should be set up. One respondent noted that there is an Entrepreneurial Physics M.Sc. option available at York University.

The other side of the coin is the role of research in the education of students. This is discussed in Sect. 22 (p. 113).

15 Encouragement by NSERC of Risk-taking

Respondents were asked what strategies should NSERC adopt regarding risk-taking [Question IV.8(a)]. Answers to this question overlap those to question IV.2(c) discussed in Sect. 12.4 (p. 90), and the comments given there apply here also.

Of the 30 respondents who answered this question, nearly all agreed that risk-taking should be an important part of the NSERC granting system. However, as in Sect. 12.4 (p. 90), the concept of risk-taking can be interpreted in two different ways. On the one hand, any vigorous research program should have a balanced mix of shorter term projects that are reasonably certain to yield useful results, and longer term projects of a more exploratory nature where the outcome is less certain (i.e. riskier). It is the latter that is more likely to lead to important new advances or insights, and certainly should be supported as one component of a larger high-quality research program.

On the other hand, risk-taking can be interpreted in the context of speculative proposals with limited chances of success whose aim is to achieve some well-defined objective, invention, or commercial application (the pay-off). The responses indicate that such proposals need to be treated with much greater caution. They should be supported only if the researcher has a good track record, based on the significance of the results and the likelihood of success. Each case should be judged on its own merits. Some of the specific suggestions are:

- Fund such proposals from separate envelopes that have no effect on research grants/scholarships, or earmark a certain percentage of the GSC budget for this purpose.
- Establish a bank of especially well qualified referees to evaluate such proposals.
- Funding should be sought from the private sector through a Collaborative Research Grant etc. if there is an obvious commercial application or pay-off.
- Encourage bottom-up proposals from self-defined research communities, rather than directing initiatives from the top down.
- Adopt a project style of management with specific goals and objectives to be met after specified time increments, and cut off funding if appropriate.

16 Role of NSERC in Spin-off Activities and Ventures

Respondents were asked what strategies should NSERC adopt regarding encouragement of spin-off activities and ventures [Question IV.8(b)]. Most respondents interpreted this to mean the formation of a high-tech company to capitalize on a discovery or invention. Although they cited many examples of this elsewhere in the questionnaire, and stressed that this is an essential part of the contribution of physics research to the Canadian economy, the vast majority of those who answered (19 out of 26) felt that this was already appropriately emphasized by various programs of NSERC, or that it was not NSERC's role in the first place (see Table 19). The main arguments were:

- The financial incentives of a successful spin-off venture already provide sufficient encouragement in the current funding environment. Industry, rather than NSERC, should be taking the initiative.
- As soon as a project is ready to take off, other agencies should step in to provide venture capital.
- The principal aim of university research is to train people with the best projects and facilities. Ventures into the business world are secondary to this principal mission. It is often the students who ultimately establish spin-off companies, or transfer technological advances to industry.

Specific suggestions to encourage spin-off activities are:

- Establish an NSERC "head hunter" officer whose responsibility it would be to make connections, catalyze contracts, and seek venture capital.
- Some of the venture capital might be specifically earmarked to facilitate the transfer of technology from universities through the hiring of physics students as they graduate.
- Put less emphasis on publications as the sole measure of productivity. Much of the research related to spin-off activities is not of a publishable nature, although it may still be very challenging in the achievement of commercial objectives.

A specific piece of advice is that it is essential to learn about a company from the inside out so that the researcher can communicate with the industrial partners on their own terms of reference. Otherwise, the partners may have difficulty appreciating the significance of the new scientific development.

Several examples showing how the results and techniques of basic research have been translated into commercial opportunities or industrial applications are given in Sect. 10.2 (p. 72).

Table 19: Questionnaire responses on the encouragement of spin-off ventures by NSERC.

Response category	Number
Not the role of NSERC	14
Current programs are adequate	5
Additional emphasis is needed	7
no response	43

17 Communication of Research Results to other Disciplines and to the Public

Question IV.8(c) of the questionnaire asked respondents what strategies should NSERC adopt regarding better communication of research results to other disciplines and to the public. Of the 22 who responded, nearly all addressed the question of communication with the public, and nearly all recognized this as an important issue, though one on which it is very difficult to make significant progress.

Many of the responses centred around the creation of science programs in the media to highlight Canadian success stories. NSERC, NRC and Industry Canada might collaborate with CBC to produce regular TV broadcasts featuring Canadian research and development. Some of the other suggestions are:

- Set up a data base with information for journalists on research supported by NSERC.
- Maintain a list of speakers who are knowledgeable and able to communicate well. They should be remunerated for their time.
- Establish a fund to which researchers could apply for the support of public lectures.
- Print single-page pamphlets highlighting a recent advance and its importance to the public. The American Institute of Physics has produced about a dozen of these suitable for distribution to Congressmen and journalists.
- Set up workshops for potential users of research in industry or other disciplines.
- Set up an award of $10,000 per year to the NSERC applicant who develops the best communication strategy.
- Focus on high profile projects, such as work on the ozone hole, to elevate the image of scientific research.

18 Participation in Interdisciplinary Research

Question IV.8(d) of the questionnaire asked respondents what strategies should NSERC adopt regarding greater participation of physicists in interdisciplinary research. As with the case of "risk-taking", the term "interdisciplinary" has come to acquire a double meaning. In one sense, physics (and particularly those topics covered by General Physics) is the original interdisciplinary discipline in that the aim is to bring an ever-expanding range of phenomena from various disciplines under a common umbrella of understanding. Physics is already the *enabling* discipline in that it provides the fundamental principles, data, instrumentation and technology that find wide application in other disciplines. These applications often provide the motivation for research proposals in physics. Some subareas such as plasma physics and atmospheric physics/space science are by their very nature interdisciplinary. Good researchers in physics are constantly on the lookout for applications in other areas. In this sense, interdisciplinary research is a natural part of the progress of physics, and it is one of its strongest features.

More recently, the term "interdisciplinary research" has come to mean targeted research in which workers from different disciplines combine their expertise to solve a particular problem, often with industrial applications. In this more narrow sense, most respondents who answered the question (12 out of 16, see Table 20) felt that such initiatives should be allowed to evolve naturally, rather than being imposed by specific new NSERC programs. Such programs just encourage exercises in grantsmanship, and their success rate is not high. A better return on investment can be obtained by providing improved funding to the individual disciplines. One respondent noted that applied physicists should take the lead in setting up interdisciplinary teams since they have the knowledge to see into the contributions that fundamental science can make to industrially motivated projects. As indicated in Sect. 13 (p. 93), about 1/3 of the respondents are now involved in various collaborations with researchers in other disciplines.

One respondent recommended that NSERC should encourage greater collaboration among GSC's to enhance interdisciplinary research, and make greater use of the Interdisciplinary GSC. There are also cultural and perceptual problems in that interdisciplinary (applied) research is not seen as being as "respectable". More applied physics courses in the physics curriculum might help.

Table 20: Questionnaire responses on the encouragement by NSERC of greater participation in interdisciplinary research.

Response category	Number
Allow to evolve naturally	12
NSERC initiatives are needed	4
no response	53

19 Enhancement of the Impact of Canadian Physics Research on other Disciplines

Question IV.9 of the questionnaire asked respondents to comment on how the impact of Canadian physics research on other disciplines could be enhanced. As in previous sections (see especially Sect. 18, p. 102), answers to this question must be understood within the context that the impact is already very profound and far reaching. Many examples have already been cited. In addition, much of engineering is largely "applied physics". However, it is not specifically identified as such once one moves outside the university setting to industry because those who do it are called engineers rather than physicists. Nevertheless, much of what they do involves the application of physical principles to practical problems, including the most recent research findings involving lasers, photonics, nonlinear optics, plasma processing, detection devices, and computer modelling techniques.

With this as an introduction, many of the 18 responses to this question contained suggestions for further enhancing the impact, such as:

- Physicists are generally very skilled at computing and the mathematical modelling of physical systems, and they should be regarded as experts in these fields. More should be done to advertise the general usefulness of these skills in other disciplines. Work at McGill on mathematical models for the propagation of waves in heart tissue and techniques for the control of arrhythmia is a good example of this [see Physics Today, August (1996), pp. 40–46].
- Existing interdisciplinary conferences such as the Interdisciplinary Laser Science Conference, or the annual Waterloo Chemical Physics Symposium are very useful.
- Set up joint symposia for colleagues in other disciplines, followed by workshops on particular topics once connections have been made. NSERC could encourage this by the provision of funding.
- Invite colleagues from other disciplines to give interdisciplinary talks at the annual CAP Congress. The CAP executive could similarly take the initiative in suggesting appropriate physicists to speak at the annual meetings of other disciplines.

In general, physicists should get more directly involved with other branches of science and engineering, and demonstrate their capabilities to industry. However, most respondents viewed specific new programs by NSERC to encourage this as likely to be ineffective and overly costly relative to their benefits. What is needed is better funding for the basic NSERC programs of operating grants and equipment.

20 Major Collaborative Efforts across Discipline Boundaries

The terms of reference ask the Committee to review whether the overall health of the discipline in Canada would be enhanced by a major collaborative effort(s) across physics subdiscipline boundaries and/or between physics and other disciplines. In order to address this question, respondents were asked to identify exciting themes that are emerging (or already exist) in their own area of research, and its relationship to others (Question V.1), and themes that should be encouraged in the broader context of physics research in Canada (Question V.2). Two other related questions are V.3 on opportunities for new or continuing interdisciplinary research, and V.4 on attitudes to the role of applied research.

The answers to these questions will first be analysed in terms of principal themes and topics, where there is reasonable agreement, and then in terms of other comments and opinions on interdisciplinary and applied research.

20.1 Principal Themes and Topics

Table 21 lists the various topics mentioned by the respondents under Questions V.1, V.2, and V.3. Although many of the respondents continued to emphasize their own fields of interest for Questions V.2 and V.3, the figures listed in the last column, if not taken too literally, give a good indication of the main areas of interest and rapid development. The results can be grouped under the six broad headings:

1. Laser physics and its applications to spectroscopy, high precision measurement, cooling and trapping, and quantum correlations (20 points),
2. Atmospheric/space research and gravity (17 points),

Table 21: Questionnaire responses on exciting themes in (V.1) the respondent's own area of research, (V.2) broader context of physics research in Canada, and (V.3) interdisciplinary research.

	No. of responses			
Theme	V.1	V.2	V.3	Total
Laser physics, trapping	9	2	1	12
Advances in computing, neural networks	8	1	0	9
Optical materials, opto-electronics	3	5	0	8
Chaos and nonlinear phenomena	6	1	1	8
Hubble space data and astrophysics	5	1	1	7
Atmospheric studies	4	1	2	7
Materials and plasma processing	2	2	2	6
Fusion and plasma physics	5	1	0	6
Spectroscopy, high precision measurement	5	0	0	5
Biomaterials, medical applications	0	2	3	5
Image processing	2	0	1	3
Gravity (waves)	2	1	0	3
Clusters	1	0	0	1
Scattering (perfect scattering expt.)	1	0	0	1

3. Advances in computing and theoretical analysis, with applications to chaos and nonlinear phenomena (17 points),
4. Plasmas, plasma fusion, and plasma processing of materials (12 points),
5. Optical materials, opto-electronics, and image processing (11 points),
6. Biomaterials and medical physics (5 points).

Even at this level there are strong overlaps and interactions among the topics listed. For example, laser physics contributes to all of the topics listed, as does computer modelling and theoretical analysis.

As repeatedly stressed in this document (see especially Fig. 1, p. 3), these topics form a closely woven mesh of interacting studies. None can be considered in isolation from the others. However, all the topics can be grouped under the even broader headings of:

- Lasers and their many varied applications, together with atomic and molecular interactions, and
- Atmospheric/space research and gravity,

with advances in computing and theoretical analysis contributing to both. The results suggest (1) broad support for an initiative to advance laser science and technology in Canada, together with its many varied applications (see Sect. 11.1, p. 78), and (2) continued support for atmospheric/space research and gravity. Throughout all of this, high quality and excellence should be the guiding principles.

Underlying both these topics, and in fact all of physics, is the even broader theme of Instrumentation and Measurement Science (IMS). The advancement of physics, whether pure or applied, is largely determined by the technology for measuring things. For example, improved techniques for signal acquisition and processing allow planets to be observed around other stars, as well as advances in the telecommunications industry. Higher precision measurements of atomic transitions yield new tests of physical principles at the most fundamental level, as well as improved standards of time and frequency for telecommunications and global positioning systems. Lasers and optical devices play a crucial role in all aspects of measurement science. IMS is now officially recognized as a Topical Group by the American Physical Society, and its support in Canada properly belongs in GSC-29. It is through IMS that strong links can be built between science and industry.

20.2 Comments on Interdisciplinary Research

Respondents identified the following areas where there are excellent opportunities for interdisciplinary research:

- Physics with biology, including medical diagnostics, and broader problems involving modelling the environment,
- Laser and plasma physics with condensed matter physics in the rapidly developing fields of material science and photonics. This also involves collaborations with engineers in telecommunications.
- Atmospheric physics and astrophysics are strongly interdisciplinary by nature, and rapidly becoming more so as applications to environmental studies become more important,
- Nonlinear dynamics and chaos in connection with dissipative systems. The fundamental principles have broad application across many disciplines.

These interactions are growing stronger than ever, and are essential if more fundamental studies are to realize their potential for broader applications. There should be no artificial barriers between physics, chemistry, engineering, etc. The second and fourth items also confirm that there already exists a firm foundation for subdisciplinary collaboration between GSC's 28 and 29 in a laser science initiative, as described in Sect. 11.1 (p. 78).

However, none of the respondents saw the need for new targeted NSERC programs to encourage these developments. The researchers themselves are the best people to see new opportunities for applications in other areas. Various interactions are constantly evolving at a vigorous pace, but it is counterproductive to try and legislate them into existence through new defined NSERC programs. Other ways to encourage interdisciplinary research are discussed in Sect. 19 (p. 103). Enhanced funding should be provided through the existing program of operating grants.

20.3 Attitudes toward Applied Research

As with the discussion of spin-off ventures in Sect. 16 (p. 100), and the discussion of interdisciplinary research in Sects. 18 (p. 102) and 19 (p. 103), most of the 16 respondents who addressed this question recognized that applied research is one of the essential ways in which research in physics contributes to the Canadian economy and to the advancement of other disciplines. There is a long tradition for this which is stronger than ever today. It is exactly in this sense that general physics, along with condensed matter physics, should be regarded as the *enabling* disciplines. As already pointed out in Sect. 19 (p. 103), much of what engineers do is really "applied physics," although it is no longer called physics because those who do it in industry are largely called engineers and not physicists. Engineering applications rest on the knowledge base created by physicists. Few research proposals in physics get funded unless they are motivated by one application or another. For example, the most fundamental studies in nonlinear optics might be motivated by potential applications to laser-plasma interactions, or to the construction of high speed optical switches. The same is true of programs to calculate or measure basic atomic and molecular properties. In this sense, the distinction between pure and applied research is not very meaningful.

However, as with other currently used terms such as "risk-taking" (see Sect. 12.4, p. 90) and "interdisciplinary research" (see Sect. 18, p. 102), the term "applied research" has come to mean a mission-oriented program set up to solve some particular industrial problem, often with financial benefits in mind. In this more restricted sense, nearly all respondents were much more cautious. The dominant theme was that truly good applied work will get funded by the end industrial users, and that it is not NSERC's role to support industry by paying the cost for industrially oriented research. In fact, such a move would be counterproductive because it would eliminate research careers for physicists in industry if the work were transferred to universities. The role of NSERC should be to support good research in universities wherever it may be found, including of course good applied research if it is innovative and of high quality. The two key points to remember are that:

1. Universities have a unique mission in society for the advancement of knowledge and its dissemination through teaching. A broad-based program of creativity and discovery must be supported because this is the one area that private industry cannot support. This is the area from which dramatic new advances of the future will come, and not the kind of incremental advances that private industry can justify to their share holders.
2. Students must be allowed to evolve in the broadest way to find the limits of their abilities, and to fulfill their maximum potential. This is best accomplished in the first instance by well-motivated fundamental studies and the advancement of knowledge, but any good researcher

should be trained to be constantly vigilant for potential applications of his or her work in other areas.

In summary, applications of one sort or another are the goal of all good research, but support of a broad range of basic science in universities is essential to the continuing health of the discipline, and the training of students to fulfill their maximum potential. Work of a more applied nature should be supported if it is innovative and of high quality, but specific new NSERC programs to encourage applied research would be redundant.

21 Effect of a 15% Increase or Decrease in Funding

The terms of reference asked the Committee to consider the effects of a 15% increase or decrease in the level of research grant funding. Since such an increase or decrease would not be spread uniformly across the discipline, respondents were asked instead to consider the effects of a doubling or halving of their NSERC operating grant (Questions II.8 and II.9). Nearly all respondents (63 out of 69) answered these questions, with results as discussed in the following two subsections.

21.1 Effect of a Doubling in Funding

The various responses to the effect of a doubling in funding are classified as shown in Table 22, with many of the respondents mentioning more than one item. The general theme is that the ever increasing demands on the time of researchers to construct and maintain their own equipment, teach courses, and perform other administrative duties is making it increasingly difficult for them to undertake new initiatives and remain competitive with workers elsewhere in the world. Thus 27 of the responses indicated that they would use additional funding to support additional graduate students, postdoctoral fellows, or research associates, and 24 of them indicated specific new projects that they could undertake if they had additional manpower and funding. The new projects covered all of the major themes listed in Sect. 20.1 (p. 105). In particular, additional funding would provide the resources for the new initiative in laser physics and its applications, as described in Sect. 11.1 (p. 78). As pointed out in Sect. 9.1.2 (p. 63), it would be a natural extension of existing strengths for Canada to be making a major contribution to the development of atom lasers and their exciting possibilities for future applications. It is a fallacy to think that Canadian industry can simply import new technologies that are developed elsewhere. Without the scientific infrastructure and expertise in Canada, it is unlikely for this to happen until after the competitive edge has been lost.

Some of the specific points from the questionnaires concerning the impact of additional funding are:

- Many of the new initiatives would involve greater risk-taking on advanced projects of a more fundamental or exploratory nature. This is the kind or work that is suffering in favour of short-term projects likely to yield quick results.
- Many of the respondents felt that their current research group was at or below a critical size, and that a larger group would be more dynamic and would generate more new ideas.

Table 22: Questionnaire responses on the effect of doubling research funding.

Response category	Number
More students/PDF's	27
New research initiatives	24
Faster progress and productivity	17
Better equipment or technical support staff	5
More collaborators	4
More travel for conferences	3
Better computing facilities	2
No effect	6
No response	6

Table 23: Questionnaire responses on the effect of halving research funding.

Response category	Number
Close down research program	22
Decrease students/PDF's	21
Decrease pace of research	14
Switch to theory only	3
Eliminate computer costs	2
No effect	5
No response	6

- Collaborative work with others is often delayed due to lack of sufficient funds.
- Especially for projects in applied physics, insufficient manpower makes it difficult to match the pace of development expected by industrial collaborators.

One respondent argued that support for postdoctoral fellows is a particularly important part of a vigorous research program because they can devote all of their time to fast-breaking research, and they are very effective in training students. However, PDF positions are few and far between in Canada. They are very powerful human engines of research, and lack of sufficient support for them is having a serious adverse impact on the pace of research in Canada.

Many of the respondents identified specific cases of lost opportunities for new research initiatives because they did not have the resources to respond quickly enough. For example, the development of the high intensity KrF laser at the University of Alberta could have been completed in one year. Instead it took four years due to lack of resources, resulting in a loss of the competitive edge to workers elsewhere.

Of the six who indicated that a doubling in funding would have little effect, four were retiring and phasing out their research, one received most of his/her funding from elsewhere, and one did not want to accept more students as a matter of policy.

21.2 Effect of a Halving in Funding

The various responses to the effect of a halving in funding are classified as shown in Table 23, with many of the respondents mentioning more than one item. Nearly 1/3 of the respondents would simply give up and close down their research program. The remainder would try to carry on by decreasing their level of support for students and/or PDF's, and by decreasing the pace of their work. However, most of these felt that they would no longer be able to remain competitive with researchers elsewhere in the world, and their work would become marginalized. The adverse impact on travel would leave them unable to maintain collaborations with others, or to attend conferences.

However, the most damaging consequence would be the effect it would have on the type of research being done. It is the potential for innovation in the areas of the major themes listed in Sect. 20.1 (p. 105) that would be most affected. The surviving research programs would tend to shift toward short-term projects of an applied nature that might find industrial support. It is the broader expansion of knowledge, and the breadth of training that this gives to students, that would suffer the most. Opportunities to make the dramatic new advances of the future would be lost. The areas of laser technology, nonlinear dynamics, chaotic systems, and photonics are all rapidly developing, and these are the areas that would be most seriously affected.

Table 24: Questionnaire responses on the role of infrastructure.

Response category	Number
Machine and electronics shops	34
Computing support	9
Library facilities	4
No response	22

In purely theoretical areas of research such as general relativity, the adverse effect would be particularly great on graduate students and postdoctoral fellows because NSERC operating grants are spent largely on their salaries. Thus, a cut in the operating grants would immediately decrease the number of people in the country doing research in these areas. Furthermore, the cuts would be greater than they would appear. It takes a certain minimum research grant to enable one to hire a postdoctoral fellow. A cut which takes one below that level immediately means the loss of the whole position (sources of funds which would allow one to use partial funding from NSERC and part from elsewhere are rare, and are also under increasing pressure.)

The high degree of selectivity in the area of general relativity and gravitation (GRG) has been discussed in Sect. 12.1.1 (p. 85). ¿From the data presented there, completely cutting the grants of the lowest 25% of the GRG grantees in GSC-17 would result in a saving of less than 7%. Thus any cuts would have to borne by some of Canada's top theorists—a strange way of ensuring that Canada remains excellent in research.

A further pernicious aspect of any such cuts is their impact on our ability to attract researchers to Canada in an increasingly competitive environment. The absence of overheads, and the freedom to spend the grant without bureaucratic micro-management can be assets in the recruitment equation. Any such assets are crucial in the face of increasingly poor salaries offered by the Canadian universities. In fact, the salaries of the top Canadian researchers for 12 months are now below the level of the average 9 month salaries in many of the better U.S. universities.

In summary, since many research groups are now at or below the critical level for survival, changes in funding levels would have a disproportionately large impact. Well-placed increases would greatly increase the levels of viability and new initiatives, while further decreases would cause many programs to shut down altogether. Other ways in which research would be affected by cuts in funding are discussed in the following subsections.

21.3 Role of Infrastructure

In addition to the effects of doubling or halving the level of funding, respondents were asked to comment on the role and importance of university infrastructure in their work (Question II.10). This has a direct impact on the level of funding because an emerging trend is for cash-strapped universities to cut back on the level of services provided free of charge or at low cost, thereby placing an additional strain on research grants and the researcher's time. The 47 responses to this question uniformly indicated that infrastructure of one form or another is of vital importance to their work. The responses are classified in Table 24. Of the 34 who focused on the machine and electronics shops, about 1/3 complained specifically about the diminishing or nonexistent levels of service available, and the additional strain that this places on their resources for research. Only one respondent indicated that the present facilities are satisfactory. It is clear that the former Infrastructure Grants program is sorely missed, and that further cuts to operating grants would

Table 25: Questionnaire responses on the role of large central facilities.

Response category	Number
Supercomputer facilities	3
Tandem accelerator	2
Tokamak	2
Laser facilities	2
Synchrotron (Wisconsin)	1
Other	3

have disastrous consequences for the ability of researchers to obtain technical services.

21.4 Role of Large Central Facilities

Respondents were also asked if large central facilities such as synchrotrons play an important role in their research (Question II.11). Only 13 of the 69 respondents indicated that they make use of large central facilities (other than those already working on location), but for these, travel is an absolutely essential part of their work that would be adversely affected by a cut in operating grants. The responses are summarized in Table 25. Only three respondents mentioned supercomputer facilities (for whom travel is not necessary), but many others expressed a need for supercomputer facilities as discussed in the following subsection. Support for the Canadian Light Source proposal is discussed in Sect. 11.2 (p. 82). Many more would undoubtedly use it if it were available.

While respondents involved in atmospheric/space research suggested that they did not use large facilities, this answer needs to be considered in the context of how they make their observations. For many in the community there is the need for space borne instrumentation. As this must be launched, there is necessarily a use of special large facilities required for such launches and the obvious satellite bus that carries the instruments. The lack of responses in this area therefore does not properly represent the needs of the community.

21.5 Role of Large Scale Computing Facilities

Respondents were asked if their research could benefit from large scale computing facilities (Question II.12). Of the 20 who responded affirmatively, about half needed supercomputer facilities for simulations of chaotic systems or for plasma modelling projects. Since only three of the 20 are currently using supercomputer facilities elsewhere, it is likely that many more would make use of them if they were more readily available in Canada. Two of the respondents argued that there is a need for more workstations in the upper price range ($100k) since they are more accessible to users than central facilities, and may in the long run be more cost effective. However, either way, large scale computer modelling projects of this sort would be curtailed by further cuts in the levels of funding.

22 Role of Research in the Education of Students

Respondents were asked several questions concerning the role of students in their research programs, and the role of research in the education of students. Table 26 shows the numbers of M.Sc. and Ph.D. students graduated in the past five years, and the total of both for each respondent. The distribution is broad and flat up to about six students graduated, and then drops down to zero beyond about 12 students (although one respondent reported a remarkable 20 students). The distributions contain a total of 225 students, divided between 118 M.Sc. students and 107 Ph.D. students.

Of the 118 M.Sc. students, 71 (60%) reportedly have jobs in physics or a closely related discipline, with 70 working in Canada and one abroad. The employment statistics are substantially better for the Ph.D. students. Of the 107 students, 99 (93%) reportedly have jobs in physics or a closely related discipline, with 61 working in Canada and 38 working abroad.

Research clearly plays a central role in the education of graduate students. The kind of "small physics" research projects typically supported by GSC-29 is ideally suited to this purpose because students become involved in all aspects of an experiment from the initial design and construction to the taking of data and subsequent analysis. In the process, they learn a broad range of skills that can be directly transferred to high technology industry, as discussed in Sect. 10.2 (p. 72). The same is true for students involved in theoretical projects, which typically involve a blend of mathematical analysis and computer programming.

However, nearly all respondents reported that they also involve undergraduate students in research projects, either as summer students or through honours thesis projects (Question VI.6). Although the demands in time can sometimes be great, most respondents were enthusiastic about the beneficial effects that an involvement in research can have in stimulating the interest of under-

Table 26: Numbers of M.Sc. and Ph.D. students graduated in the last five years, from a pool of 53 out of 69 responses.

	No. of responses		
No. of students	M.Sc.	Ph.D.	Total [a]
0	12	17	6
1	10	10	8
2	13	8	8
3	5	8	5
4	2	2	5
5	5	5	7
6	3	1	4
7	1	1	3
8	0	0	2
9	1	0	2
10	0	0	2
11	0	0	0
12	0	1	1
20	0	0	1

[a] "Total" is the number of responses for the given total number of students. For example, 12 respondents had 0 M.Sc. students, 17 respondents had 0 Ph.D. students, and 6 respondents had 0 students in total for the past five years.

Table 27: Questionnaire responses on the effects of research on teaching. Do you think that your involvement in research makes your teaching ...

Response category	Number
much better	37
better	25
the same	1
worse	1
much worse	0
no response	5

graduate students. The projects often result in publishable work. Research also enters in a more indirect way in that it brings lectures alive with examples drawn from personal experiences. The answers to Question VI.7 on how involvement affects teaching are summarized in Table 27. The vast majority thought that involvement in research made their teaching "better" or "much better", with over half in the latter category. This provides a clear foundation for the view expressed in Sect. 12.3 (p. 89) that a broad base of research should be supported in all universities in order to maintain the quality of undergraduate as well as graduate teaching. It has sometimes been argued that research distracts university faculty from their teaching duties. On the contrary, good teaching and good research go hand-in-hand.

In answer to Question VI.8, respondents clearly identified the unique benefits that a student should obtain from a physics education. The large variety of answers can be summarized as follows. Physicists have a unique versatility and adaptability stemming from their broad understanding of the fundamentals, training in critical thinking, and problem solving skills. They have a general familiarity with the techniques of high technology, and the ability to teach themselves new things as the need arises. They are adept at forming mathematical models of systems and drawing logical conclusions from them. Their education has exposed them to the frontiers of human knowledge about the physical universe.

The role of students in technological transfer is discussed in Sect. 14.1 (p. 97).

23 Vision for the Future

This document has discussed the ways in which the topics covered by GSC's 17 and 29 form a closely woven mesh tied together by common bonds of underlying theory and experimental technique. Most importantly, the topics are tied together by closed loops of fundamental studies and applications. For example, basic atomic data and studies of nonlinear phenomena contribute to the design of better laser systems; and improved lasers provide a new tool to study basic atomic and molecular interactions, as well as atmospheric phenomena, plasma interactions, surface interactions, and the detection of gravity waves. The chain of interactions would be broken if any element were removed. The diversity of topics covered should be regarded as a strength flowing from the generality of the experimental and theoretical techniques employed. That is why it is called "General Physics". Diversity is a sign of a healthy discipline capable of responding quickly to new initiatives.

23.1 Vision for General Physics

The single most important new initiative for General Physics identified in this study follows from the dramatic and relentless advance of laser science and technology, and an equally dramatic and relentless advance in the power of computers. Each new generation of laser capability and computer power opens up new territories for fundamental study and technological application. A new initiative in laser science and spectroscopy is discussed in greater detail in Sect. 11.1 (p. 78). The historical roots of Canadian physics in spectroscopy, optics, plasma physics, and atmospheric physics/space science would be drawn together by this proposal. A firm foundation already exists in these areas, and in the closely related areas of condensed matter physics covered by GSC-28 (the connections with GSC-28 are further discussed in Sect. 1.1, p. 2), and mathematics.

The potential for both fundamental studies and technological/industrial applications in other areas is enormous, such as surface science, photonics, plasma physics and laser fusion, chemical kinetics, and medical applications. However, substantial new investment in funding is required to make significant progress. The survey results indicate that past cuts in funding have left many research groups at or below the critical level of viability, and their research is becoming marginalized relative to their competition elsewhere in the world. It is the longer term higher-risk research done in universities that is most likely to yield dramatic new advances, but this is the type of research that suffers the most as funding levels decline (see Sect. 21, p. 109). The training of students suffers correspondingly as researchers curtail this type of work, and universities are no longer able to fulfill their mandate for the creation of the fundamental new knowledge upon which technological applications are based.

The field is constantly being revitalized by advances in laser technology and computer power. A substantial new investment in laser science through the NSERC operating grant program would similarly revitalize Canadian physics and its potential to make important new contributions. The effect would be strongly interdisciplinary, involving not only condensed matter physics and mathematics, but also a wide range of other disciplines and industrial applications where the laser is a tool of ever growing importance.

23.2 Vision for Atmospheric Physics and Space Science

In almost every case the respondents see the research efforts in atmospheric and space physics as leading to an improved understanding of the geospace environment. There is also a belief that the future in physics research should build on existing strengths and not simply enter a new area because it is in vogue. (This does not preclude the need for curiosity driven research). For the atmospheric researchers this translates into the ability to make measurements that will allow reliable forecasting (essentially there is an implied notion of applied research). These forecasts apply to space weather as well as the atmosphere, both of which will benefit from our new knowledge of geospace. It is anticipated that the area of space weather study will be a major theme for many nations as the role of satellites in our everyday lives increases. The loss of coast-to-coast TV following the large solar storm earlier this decade is only one example of the need for space weather forecasts. However, if we are to achieve this improved knowledge, there will be an expanded need for enhanced data processing techniques. This means that data will be transmitted in "real-time" to analysis sites that will produce immediate complete analyses rather then quick look summary plots. It will also require an improvement in the information highway. It is now probable that the goal of using real time satellite monitoring to provide airlines with information that can save fuel costs will be achieved by this research.

All of this can be summarized by saying that the encouragement of space and atmospheric physics will not only improve our knowledge of the environment, but will also have significant spin-off effects. Perhaps it is because physics is so diverse that it has such a wide impact in many areas and consequently makes the world go round.

23.3 Vision for General Relativity and Gravity

Why should the government fund a field like general relativity or gravity? It has been regarded even in the physics community as esoteric, and certainly has little chance for technological spin off. However, Canada is more than its technology and more than its natural resources. Canada is a country with aspiration and with the potential to be a world leader in many areas. Together with this must come a demonstration of world leadership in certain select areas. The research into general relativity, gravity and cosmology is one of the areas in which Canada at present is an emerging world leader. A country which can point to its ability to solve the most difficult questions about the universe in which we live will also have the necessary self confidence to tackle and solve the practical problems which beset us here on earth.

Gravity and cosmology are recognised by the public as amongst the most exciting areas in the world. A day does not go by without news stories about recent astronomical or cosmological advances. Furthermore, the country can obtain its international lustre at a cheap price. By concentrating on theory, Canada has, and will be able to create a far greater international impact for a given dollar than it would if it also had to fund the expensive experiments. Of course this is only possible if those same theorists maintain the closest of ties with the experimental efforts elsewhere, and maintain at least a minimal level of experimental expertise here as well. It is also an argument which neglects the technological spin-offs that a strong experimental program brings. But it is an argument which we feel does suit the field of gravity research. Thus we do not advocate either the establishment of gravity experiments in Canada, or financial investment in foreign ones at the present time. However, we do strongly recommend that a Canadian presence be maintained and strengthened in theoretical general relativity so that Canada can share in the most exciting intellectual venture of our age.

Acknowledgments

We are grateful to the many members of the General Physics, Atmospheric Physics, Space Science, and General Relativity communities who took the time to respond to our questionnaire. We are also grateful for the many valuable responses to our initial *Draft for Discussion*, which have helped immeasurably in producing a more comprehensive document. This document would not have been possible without the able assistance of the staff at NSERC and CAP, and financial support from

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A Funding of Academic Research in Canada

Canadian university-based researchers in the fields covered by this report obtain support from six principal sources:

1. the Natural Sciences and Engineering Research Council (NSERC) (by far the largest source),
2. the Canadian Space Agency (CSA) (for Atmospheric and Space Science),
3. internal university funds,
4. Provincial government programs,
5. the Canadian Institute for Advanced Research (CIAR),
6. industry (often coupled with leveraged NSERC 'partnerships program' support).

In addition, the Killam Foundation (administered by the Canada Council) provides Fellowships which relieve faculty members of their teaching duties for a period of two years, thereby allowing them to devote all of their time to research. Typically, two or three of these are awarded per year in the general area of Physics.

While NSERC, CSA, and CIAR programs are national in scope, the other sources vary widely from province to province. Traditionally, NSERC has provided Research Grant support for equipment, personnel, expendables and other direct costs of research, while the universities have provided the majority of support for basic infrastructure (e.g. workshops, technicians, utilities etc.). NSERC's Research Grant program provides the majority of support for university-based research in Canada, and is discussed in further detail below. NSERC also has project-oriented programs; some stand-alone, such as Research Partnerships (which involve partnering with a non-university collaborator—usually industry but potentially also a government laboratory), and some that they administer on behalf of other government agencies such as the National Research Council.

NSERC also coordinates 14 Networks of Centres of Excellence (NCEs) that help support groups of researchers working on specific topics deemed to be of particular importance to the country. The total budget for the current phase of this program is $197 million over five years. The organization and procedures of the NCEs vary, but all are heavily involved with industrial partners, and all coordinate the exchange of information and ideas among participating researchers and industrial affiliates. At present, these do not provide direct support for the areas covered by this report.

In Atmospheric Physics and Space Science, projects funded by the CSA require a formal industrial partnership for such things as the design and manufacture of payload instrumentation packages. Also, the projects are often too large to be handled by a single institution. For these reasons, collaborative projects with industry and other institutions play a particularly prominent role. The industrial connections are further discussed in Sect. 6.1.1 (p. 37).

The Canadian Institute for Advanced Research (CIAR) is a nongovernmental organization that owes its existence to Fraser Mustard, a social and scientific visionary. Since its inception in 1982, the CIAR has supported "research institutes without walls", that have influenced the development of science and technology throughout Canada, as well as public and private policies in health, science and technology, economics and human development. There were nine separate programs supported in 1996:

1. Population Health
2. Human Development
3. Economic Growth and Policy
4. Cosmology

5. Evolutionary Biology
6. Earth Systems Evolution
7. Artificial Intelligence and Robotics
8. Science of Soft Surfaces and Interfaces
9. Superconductivity.

Program 'members' include the top researchers in these nine targeted fields; most are from Canadian universities, but others come from all parts of the world. Members receive financial support from the CIAR that enables them to dedicate more time to research at their home institutions, to visit their colleagues and have their colleagues visit them on a more frequent basis, and to run small, focused workshops on topical subjects on a regular basis. As of June 1996, the CIAR had raised more than \$62 million, 34% from the private sector, 27% from provincial governments, and 39% from the federal government, or an average of \$4.5 million per year. The General Relativity and Gravity research community has benefited greatly from participation in the CIAR Cosmology program (see Sect. 7.3.1, p. 46). In addition to the obvious advantage of having more time to devote to research, the networking and regular meetings have had a very positive effect on establishing a sense of community in these areas, and in enhancing their international impact.

The provinces of Ontario and Quebec have special programs that support groups of researchers working on related topics. Of particular relevance to this report are the Ontario Laser and Lightwave Research Centre (OLLRC) supported by the Ontario Centres of Excellence program (see Sect. 2.2.1, p. 8, and Sect. 4.1, p. 25), and the Centre de Recherches Mathématiques (CRM) supported in part by les Fonds pour la Formation de Chercheurs et l'Aide a la Recherche (FCAR) respectively (see Sect. 2.2.3, p. 12). These two programs differ a great deal in their organizations, but both have a significant impact on General Physics research in those provinces. Some of the other provinces have smaller programs that typically require very direct industrial participation, and offer little prospect of funding continuity. Direct industrial support for university-based physics research is small in comparison with NSERC support.

There is a number of smaller companies that collaborate with university-based researchers on targeted projects. NSERC has several programs that will match both cash and in-kind contributions from industrial partners. These include Strategic Project Grants, Industrially Oriented Research Grants, and Collaborative Research and Development Grants. For a few researchers, particularly in the areas of optics, lasers and semiconductors, the total support from industry plus the NSERC matching and strategic programs can equal or exceed their basic Research Grant funding. However, this type of funding typically does not have the continuity and predictability which are widely seen to be among the most positive aspects of the Research Grants program. Several examples of industrial "success stories" are discussed in Sect. 10.2 (p. 72).

There are three other NSERC-administered programs that should be mentioned, before focusing on the Research Grants component. The first is funded by NRC and has existed for only one year. Its objective is to support the university component of collaborative projects involving NRC, the university group(s), and small (¡ 500 person) companies. As it covers the entire NRC and NSERC mandate, there will likely be at most one General Physics project funded per year. The Technology Partnerships Program has similar goals, but it is funded by NSERC, and it does not necessarily involve the participation of government laboratories. The specific purpose is to help transfer university-generated technology to small and medium sized Canadian companies. Finally, there is also a Research Networks Program that involves partnering with at least one non- university collaborator (while industrial participation is not a formal requirement, it can be assumed to be near-essential). This program appears to be in lieu of future competitions for new Networks of

Centers of Excellence. It is specifically for research opportunities where there is a demonstrable benefit to a network approach that links at least five researchers from three different institutions.

A.1 The NSERC Research Grants Program

The overwhelming majority of NSERC support for General Physics comes through the Research Grants and the Scholarships programs. A researcher may only be a principal investigator in one NSERC Research Grant at a time, whether it is an individual grant or a team grant. The Research Grants program is designed to support high quality research regardless of any direct or short term economic justifications. It is a flexible program that emphasizes the quality and impact of past and proposed work, and puts few constraints on how the awards are used to achieve these goals. Research Grant applications do not require milestones, and there are no penalties for fruitful changes in research direction in the middle of a grant (which normally lasts four years). When applying for the renewal of a Research Grant (funding under this program has a high degree of continuity), the success over the previous grant period is not judged against the goals of the previous grant application, but rather by attempting to evaluate the achievements (publications, impact, excellence, training) on their own merits. As a general rule, the track record is much more important than the details of the research proposal, which encourages changes in research direction and the undertaking of novel or 'high risk' projects.

Research Grant applications are reviewed by a number of discipline-based Grant Selection Committees (GSCs) that cover a wide range of subjects, from psychology to subatomic physics. The most recent available breakdown of NSERC Research Grant and Equipment expenditures by GSC are listed in Table 28. Each GSC is comprised of academic and industrial researchers from Canada and abroad.

An important difference between NSERC Research Grants in Canada and similar grants in the U.S. is that no overhead may be paid from NSERC grants, and no part may be used toward the salary of regular faculty members. This makes a substantial difference when comparing the sizes of grants in Canada with those held elsewhere. A detailed listing of NSERC grants for GSCs 17 and 29 is given in Appendices C to 37.

The GSCs operate within their budget envelopes with a fair degree of freedom. They are constrained by the NSERC regulations and guidelines, but there is substantial flexibility based on the interpretation of these guidelines. The four criteria for evaluating Research Grant (and equipment) proposals are:

1. Scientific or engineering excellence of the researcher(s),
2. Merit of the proposal,
3. Need for funds (or equipment),
4. Contribution to the training of highly qualified personnel (HQP).

Research Grant applications consist of two parts. The first contains the budget, plus a five page description of the progress made during the last grant cycle, and the work proposed for the next cycle. The second, or personal data form, summarizes and quantifies the applicant's research contributions over the previous six years. Equipment Grant requests include the same personal data form, and an application form that describes the equipment, and budget, and explains the intended use. Minor equipment applications are limited to two pages of text, major equipment applications to 10 pages, and major installation proposals are open-ended.

NSERC also provides a limited number of scholarships for graduate students and postdoctoral fellows. Some provinces and/or universities also have graduate student scholarship programs. Together, this means that approximately 30% of graduate students have some sort of scholarship that

Table 28: NSERC research program grants awarded in the 1996 competion [from NSERC Contact, **21**, No. 2, p. 7 (1996)].

	Research[a]		Equipment[b]		MFA[c]		Total	
GSC	*N*	k$	*N*	k$	*N*	k$	*N*	k$
Animal Biology	235	5,899	19	530			254	6,429
Animal Physiology	200	6,627	15	428			215	7,055
Cell Biology and Genetics (02)	1	51					1	715
Cell Biology	265	8,589	23	664			288	8,786
Molecular & Developmental Genetics	171	6,644	11	197			182	6,841
Plant Biology and Food Science	305	9,728	39	1,002			344	10,730
Evolution and Ecology	451	12,573	28	596			479	13,170
Psychology	346	8,966	24	394			370	9,360
Solid Earth Sciences	299	8,880	17	708			316	9,588
Environmental Earth Sciences	333	7,998	30	1,177			363	9,175
Inorganic and Organic Chemistry	270	11,421	31	2,490			301	13,911
Analytical and Physical Chemistry	299	10,767	27	2,252			326	13,019
Space and Astronomy[d]	155	4,842	13	247	2	125	170	5,214
Condensed Matter Physics	215	6,489	25	1,156			240	7,645
General Physics	129	3,870	13	620			142	4,490
Pure and Applied Mathematics (16)[e]	4	92					4	92
Pure and Applied Mathematics A	299	4,273	2	77			301	4,350
Pure and Applied Mathematics B	223	3,167	7	167			230	3,334
StatisTical Sciences	242	3,128	12	229			254	3,357
Computing and Information Science	502	11,342	21	719	11	668	534	12,728
Communications, Computers and Components Engineering	300	6,819	11	454			311	7,273
Electromagnetics and Electrical Systems Engineering	255	6,261	17	602			272	6,863
Industrial Engineering	223	4,484	11	273	2	100	236	4,858
Chemical and Metallurgical Eng.	424	12,154	32	1,891			456	14,045
Civil Engineering	504	11,201	30	875			534	12,076
Mechanical Engineering	485	11,077	30	1,180			515	12,257
Interdisciplinary[f]	39	940	2	57	50	3,690	91	4,686
Committee on Research Grants[g]			9	4,969	1	30	10	4,999
Committee in Life Sciences			7	867			7	867
Total (excluding Subatomic Phys.)[h]	7174	188,283	506	24,820	66	4,612	7,746	217,912
Subatomic Physics	160	11,501	10	482	13	5,009	183	16,9921

[a]Includes individual, team, and project grants and grants to holders of Women's Faculty Awards.

[b]Includes Equipment, Major Equipment, and Major Installations Grants; some equipment grants were paid with 1995 funds.

[c]Major Facility Access Grants, including phase-out of Infrastructure Grants.

[d]Space science is also funded by the Canadian Space Agency.

[e]Remaining installments of grants from GSCs which have been eliminated by reorganization.

[f]Handles all interdisciplinary (i.e. multi-GSC) Equipment and MFA Grants.

[g]Final authority on Major Installation Grants.

[h]NSERC has historically followed this format due to the unique importance of Project Grants to subatomic physics.

effectively augments their supervisor's Research Grant. A small number of postdoctoral fellowships are also awarded, but these are often held outside of Canada. The Research Grants program therefore funds a large portion of the stipends/salaries of all research personnel (excluding professors themselves), major and minor equipment, and the direct costs of research (excluding utilities etc.).

A.2 The Reallocation Process

Starting in 1994, the distribution of the total Research Grant budget among GSCs is adjusted every four years through a Reallocation Process. In the first Reallocation, this consisted of placing 10% of each GSC's budget into a pool, and reallocating the pool based on the Reallocation Committee's review of written submissions from all the GSCs, where the supposed primary criterion was research "excellence." The CMP and General Physics GSCs made a joint submission, and together with Subatomic Physics and Mathematics, received the maximum 8.5% reduction resulting from Reallocation.

The little feedback received from the Reallocation Committee was a brief statement of their opinion that our community suffered from a lack of focus, and that the job opportunities for graduates were not the best. The present Review of Physics is timed so that the results can be used as input for the next Reallocation exercise (submissions due Jan. 1, 1998). The criteria for the next exercise will be very different from the first. Rather than focusing on generic issues of quality, discipline dynamics etc., the submissions will specifically have to address how their community would use any new resources for the "benefit of Canada." Although the General Physics community generally favoured making a joint submission for the next reallocation exercise, this opinion was not shared by the other Physics communities, partially as a result of the poor showing for all of physics in the last competition. Thus all of the Physics GSCs will make independent submissions in 1998.

The divisions along discipline lines has become even sharper with respect to the astronomy and astrophysics communities since they fared relatively better in the last reallocation exercise, and their members tend to align themselves more with CASCA than with CAP. As a consequence, with the approval of CASCA and NSERC, only the atmospheric physics and space science parts of GSC-17 are included in the present study as initiated by CAP.

A topic that is often discussed in the context of reallocation, both within the community and with NSERC representatives, is the level of "selectivity" exercised by various GSCs. There exists a perception that Physics GSCs have not been as selective as some others. There is much debate as to what, if any, hard evidence for this exists, but certainly there is the flexibility within the system to vary the degree of selectivity. This is discussed in Sect. 12.1 (p. 85).

A.3 University Support

Canadian universities have a quite different relationship to research funding as compared with, for example, those in the U.S. In Canada, the universities provide full 12- month salaries for all their faculty, even though most faculty only teach for two full terms of courses. Faculty salaries are infrequently augmented through consulting fees, but not through Research Grants or contracts. The universities can collect overhead only on research contracts, but not on NSERC Grants of any kind. Thus the universities provide full salaries to the faculty, whether they are active in research or not, and must cover from their own resources some of the costs inherent in research (buildings, utilities, technical support).

The universities also often provide significant startup support for new faculty, depending upon their financial resources and their willingness to hire competitively. Many universities have some form of internal operating support for research, but these tend to be of minimal size.

Canadian universities, under increasing economic pressure, inevitably begin to see the winning of Research Grants, and even more so large Equipment and Installation Grants, as a significant cost rather than a benefit to the university, offset only by the intangible prestige which a vigorous research program can bring. In this environment, university support for existing facilities, and the willingness to commit to support in order to win new facilities, becomes an ever greater problem.

A.4 The Growing Crisis in Infrastructure Support

In Canada, the provincial governments are responsible for and control education, but the financial resources come primarily from the federal government in the form of "transfer payments". These transfer payments are the principal source of university budgets, a portion of which has traditionally been used to support research through such things as technician's salaries, workshop equipment, startup funds etc. Transfer payments have been substantially reduced over the past five years, resulting in continuing budget cuts to the universities. Institutional support for research is thus constantly declining, as shrinking resources are concentrated more and more on the direct costs of teaching. The federal government has also reduced the NSERC budget over the past five years, forcing NSERC to cut all of their "non-core" programs. The net effect is that the Research Grant budget has remained almost constant, in absolute dollar units, while the pool of eligible researchers continues to grow. Worse, the support for infrastructure, undergraduate summer fellowships, and new programs such as the Collaborative Project Grants has either been substantially reduced, or completely abolished. In particular, while the infrastructure requirements for research have been steadily increasing, the sources for appropriate funding are rapidly drying up. Unfortunately the provincial governments, in spite of their responsibility for funding and operating the higher education system, have shown little interest in addressing the infrastructure problem. This problem is further discussed in Sect. 21.3 (p. 111).

B Honours and Awards

This Appendix lists certain selected types of honours, awards, and other forms of distinction for researchers supported by GSC's 17 and 29. Only those items that cut across either subdisciplines or international boundaries are included.

Table 29: Fellowships in various societies.

APS	OSA	IEEE	FRSC	FRS
		GSC-29		
Baylis, W.E.	Arsenault, H.H.	Hirose, A.	Carswell, A.I.	Stoicheff, B.
Drake, G.W.F.	Chin, S.L.	Smith, P.W.E.	Corkum, P.[b]	Watson, J.K.G.[b]
Hirose, A.	Délisle, D.		Drake, G.W.F.	
Krause, L.	Dugay, M.		Gray, C.G.	
Mandelis, A.M.	Joshi, Y.		Marmet, P.	
McConkey, J.W.	Lessard, R.A.		McKellar, A.R.W.[b]	
Pinnington, E.	Lit, J.		Stoicheff, B.P.	
Reddy, S.P.	Smith, P.W.E.			
Schlesinger, M.	Stoicheff, B.P.			
Stauffer, A.D.	Van Driel, H.[a]			
Stoicheff, B.P.				
Varshni, Y.P.				
Watson, J.K.G.[b]				
		GSC-17		
Nicholls, R.W.	Nicholls, R.W.		Bond, J.R.	Israel, W.
			Israel, W.	Tremaine, S.D.
			Llewellyn E.J.	
			Nicholls, R.W.	
			Rostocker, G.	
			Shepherd, G.G.	
			Tremaine, S.D.	
			Unruh, W.G.	

[a]Supported by GSC-28.

[b]NRC scientist not supported by NSERC.

Table 30: Selected awards and prizes.

Killam Fellow	CAP Medal	Herzberg Prize	CAP-CRM Prize	Steacie Prize
		GSC-29		
Drake, G.W.F.	Corkum, P.[a]	Drake, G.W.F.		Drake, G.W.F.
McConkey, J.W.	Drake, G.W.F.	Marmet, P.		
Offenberger, A.	Stoicheff, B.P.	McKellar, A.R.W.[a]		
Ozier, I.				
Patera, J.				
Van Driel, H.[b]				
		GSC-17		
Shepherd, G.G.	Israel, W.	Kaiser, N.	Israel, W.	Unruh, W.
Tremaine, S.D.	Unruh, W.	Unruh, W.	Unruh, W.	

[a]NRC scientist not supported by NSERC. [b]Supported by GSC-28.

Table 31: Other awards and distinctions.

Name	Award	Date
	GSC-29	
Chin, S.L.	Science Achievement Award, Chinese Can. Inst. Arts & Sci.	1988
Lit, J.	Science Achievement Award, Chinese Can. Inst. Arts & Sci.	1989
Hessels, E.	J. C. Polanyi Prize	1993
Hirose, A.	Distinguished Foreign Researcher, Japan At. Ener. Res. Inst.	1995
Hirose, A.	Merit Award, IEEE Nucl. Plasma Sciences Soc.	1993
Smith, P.W.E.	IEEE Quantum Electronics Award	
Stoicheff, B.P.	Henry Marshall Tory Medal (Roy. Soc. Can.)	1989
Stoicheff, B.P.	Frederic Ives Medal	1983
Stoicheff, B.P.	William Meggers Medal	1981
van Driel, H.[a]	J. S. Guggenheim Fellow	1986
van Driel, H.[a]	Alexander von Humboldt Prize	1989
Watson, J.K.G.[b]	APS Earl K. Plyler Prize	1986
	GSC-17	
Bartel, N.	Otto Han Medal (Germany)	1979
Bond, J.R.	Steacie Fellow	
Hocking, W.K.	Pansey Medal for Physics, Australian Acad. Sci.	
Israel, W.	Officer of the Order of Canada	
Israel, W.	Killam Prize	
Israel, W.	CAP/CRM Mathematical Physics Prize	
Kaiser, N.	Steacie Fellow	
Kaiser, N.	AAS Warner Prize	
Llewellyn, E.J.	Am. Geophys. Union Excellence in Refereeing Award	1989
McDade, I.C.	Am. Geophys. Union Excellence in Refereeing Award	
Poisson E.	Plaskett Medal	1992
Tremaine S.	CASCA Dannie Heinemann Prize	
Tremaine S.	Rutherford Medal	
Unruh, W.	Killam Prize	
Unruh, W.	Steacie Fellow	
Unruh, W.	CAP/CRM Mathematical Physics Prize	

[a]Supported by GSC-28.

[b]NRC scientist not supported by NSERC.

Table 32: Editorial positions.

Name	Position	Journal	Dates
		GSC-29	
Arsenault, H.H.	Editorial Board	J. Mod. Optics	
Ballentine, L.E.	Editorial Board	Phys. Rev. A	1993–96
Baylis, W.E.	Int'l Editorial Board	Adv. Appl. Clifford Alg.	1993–96
Drake, G.W.F.	Divisional Associate Editor	Phys. Rev. Lett.	1985–94
Drake, G.W.F.	Editorial Board	Phys. Rev. A	1991–97
Drake, G.W.F.	Co-editor	Can. J. Phys.	1997–
Lessard, R.	Associate Editor	Opt. Mem. Neural Networks	
Lessard, R.	Associate Editor	J. Infrared Millimeter Waves	
Lessard, R.	Associate Editor	Photonics Science News	
Lessard, R.	Editor	SPIE Review Volumes	1990–
Lit, J.	Associate Editor	J. Opt. Sci. Am.	1974–79
Hirose, A.	Associate Editor	IEEE Trans. Plasma Sci.	1984–
Holt, R.A.	Divisional Associate Editor	Phys. Rev. Lett.	1994–
Mandelis, A.M.	Associate Editor	Rev. Sci. Instr.	1997–
Mandelis, A.M.	Editorial Board	Int'l J. Thermophys.	
Mandelis, A.M.	Editorial Board, Analyt. Sci.	J. Jap. Soc. Analyt. Chem.	1994–00
McConkey, J.W.	Int'l Advisory Comm.	J. Phys. B	1992–
McKellar, A.R.W.[a]	Editorial Board	J. Chem. Phys.	1995–97
Offenberger, A.A.	Editorial Board	Laser & Particle Beams	1987–
Patera, J.	Editorial Board	J. Math. Phys.	1984–86
Patera, J.	Editorial Board	J. Alg. Groups, Geom.	1984–86
Piché, M.	Editorial Board	Opt. Commun.	1997–
Schlesinger, M.	Co-editor	Can. J. Phys.	1997–
Smith. P.W.E.	Editor-in-Chief	Optics Lett.	1989–96
Vallée R.	Editorial Board	Opt. Commun.	1993–
van Driel H.	Topical Editor	J. Opt. Soc. Am.B	
Watson, J.K.G.[a]	Editorial Board	Mol. Phys.	1979–
Watson, J.K.G.[a]	Editorial Board	J. Mol. Spectrosc.	1972–
Watson, J.K.G.[a]	Editorial Board	J. Chem. Phys.	1991–93
Winternitz P.	Associate Editor	J. Math. Anal. Appl.	1992–95
		GSC-17	
Bartel, N.	Editor, Vol. 224	Lecture Notes in Phys.	1984
Caldwell, J.	Editorial Board	Icarus	1982–84
Llewellyn E.J.	Editorial Advisory Board	Planetary Space Sci.	1982–92
Manson, A.H.	Editorial Advisory Board	J. At. Terr. Phys.	1986–92
Nicholls, R.W.	Editor	Can. J. Phys.	1986–92
Nicholls, R.W.	Associate Editor	J. Quant. Spec. Rad. Trans.	1960–

[a]NRC scientist not supported by NSERC.

Table 33: Leadership positions in scientific organizations.

Name	Position	Dates
	GSC-29	
Arsenault. H.H.	V.P. and President of SPIE	1993–95
Arsenault. H.H.	V.P. of ICO	1988–96
Arsenault. H.H.	Chair, ICO Div. of Information Processing	1995–96
Bélanger P.A.	Consultant on Eureka project	1994–96
Carswell, A.	President, CAP	
Chin, S.L.	Founding Chair of the OSA Internat. Activities Comm.	1986–87
Chin, S.L.	Chair of the OSA Mees Medal Committee	1987–88
Drake, G.W.F.	Chair, Atomic, Molec., Optical Physics Division, APS	1996–97
Drake, G.W.F.	Chair, Commision C15 of IUPAP	1994–
Drake, G.W.F.	Advisory Board, Harvard-Smithsonian ITAMP	1995–98
Hirose, A.	Member, U.S. DOE Peer Review Committee	1992
Lessard, R.A.	President of CAP	1994–95
Lessard, R.A.	Board member of SPIE	1995
Lessard, R.A.	Awards Committee of SPIE	1995–97
Lees, R.M.	President, CAP	1993–94
Lit, J.	Founding Pres., S.W. Ont. Sect., Opt. Soc. Am.	1994–95
Mandelis, A.M.	Exec. Instrum. Meas. Sci. Topical Group of APS	
Marmet, P.	President, CAP	
Offenberger, A.	Consultant to LLNL	
Offenberger, A.	President, CAP	1990–91
Smith, P.W.E.	Pres., Lasers and Electro-Optics Soc. (IEEE)	1984
Smith, P.W.E.	Chair, OSA Board of Editors	1996–98
Stoicheff, B.P.	President, CAP	1984–85
Stoicheff, B.P.	V.P. of IUPAP	1993–96
Stoicheff, B.P.	President, Optical Society of America	1976
	GSC-17	
Atkinson, G.	Division III Leader, IAGA	
Bartel, N.	Co-chair, Harvard-Smithsonian CFA Workshop	1984
Bartel, N.	Advisor, German Aerospace Res. Est.	1989
Caldwell, J.	Hubble Space Telescope Scientist	1990–97
Llewellyn, E.J.	Member, NASA Timed Sci. Definition Team	1990–91
Manson, A.H.	Member, Steering Comm. for Post-STEP Int'l Progs.	1995–02
Manson, A.H.	Chair, Subcommision C2 of COSPAR	1994–98
Nicholls, R.W.	Past President of Commission 14 of the IAU.	
Nicholls, R.W.	Member of Science Team of TRACER (NASA)	
Nicholls, R.W.	Founding Chairman of CACSUSS	1985–89
Rostocker, G.	V.P., IAGA	
Rostocker, G.	Chair, STRP Steering Committee (SCOSTEP)	1992–97
Rucinski, S.	Canada-France-Hawaii Telescope Time Allocation Com.	1990–92
Rucinski, S.	Hubble Time Allocation Panel	1993
Shepherd, G.G.	Convenor, SCOSTEP PSMOS Program	1997–02
Sofko, G.J.	Exec. Council of PI's for SuperDARN	1992–97

C Tabular Summaries of Research Programs for GSC-29

The following tables summarize the research programs funded by GSC-29, ordered by institution (Table 34), and by field of study (Table 35). The various subfields are defined as follows:

- AM – Atomic and Molecular physics, including spectroscopy, atomic and molecular structure, collisional interactions and dynamics.
- PL – Plasma physics, including controlled fusion and laser-plasma interactions.
- LA – Laser physics particularly focused on laser development as opposed to laser applications.
- OP – Optical physics, including quantum optics, optical devices, fibre optics, image processing, photonics, laser applications, and nonlinear phenomena.
- FD – Fundamental theory of a broad and general nature, including field theory, quantum electrodynamics, chaos, nonlinear systems, and statistical mechanics.
- MP – Mathematical Physics, including topics of a general mathematical nature such as group theory, and the solution of systems of differential equations.

In addition, each subtopic is divided into theory and experiment.

Table 34: Research programs funded by GSC-29, ordered by institution.

University	Field	Name	Amount	Description
Acadia	PL-E	MacLatchy, C.S.	7 000	Applications of lagmuir probes in plasma diagnostics.
		Total grants:	7 000	
Alberta	FD-T	Tuszynski, J.A.	15 000	Nonperturbative field theory and self organization.
Alberta	AM-E	Pinnington, E.H.	50 000	Atomic physics using fast ion beams (group).
Alberta	AM-E	Smy, P.R.	20 000	Combustion physics.
Alberta	AM-T	Razavy, M.	12 000	Multi-dimensional quantum tunneling with and without dissapative coupling.
Alberta	AM-T	Spanos, T.J.T.	7 000	Physics of megascopic mixtures and macromolecular systems.
Alberta	AM-T	Stephenson, J.	6 000	Modelling in non-linear dynamics and statistical mechanics.
Alberta	PL-E	Fedosejevs, R.	48 000	High intensity picosecond and femtosecond UV laser-plasma interactions.
Alberta	PL-E	Offenberger, A.A.	70 000	High field physics.
Alberta	PL-T	Capjack, C.E.	25 000	Simulation of laser plasma interactions.
Alberta	PL-T	Rozmus, W.	30 500	Theoretical plasma physics–Laser plasma interactions.
		Total grants:	283 500	
UBC	FD-T	Ahlborn, B.	10 000	Vortex Dynamics.
UBC	AM-E	Auerbach, D.E.	26 000	Chaotic dynamics, control and correlations in spatially extended systems.
UBC	AM-E	Balzarini, D.A.	10 000	Optical studies of phase transitions in pure fluids, binary fluids and liquid crystals and electron momentum spectroscopy.
UBC	AM-E	Ozier, I.	42 000	High resolution molecular spectroscopy: magnetic rotation, ions, and large amplitude motion.
UBC	PL-E	Meyer, J.	46 200	Laser plasma interactions and ultrashort pulse laser physics.
UBC	PL-E	Ng, A.	58 000	Physics at high energy density.
		Total grants:	192 200	
Carleton	AM-E	Johns, P.C.	15 000	Medical X-ray imaging physics research program.
Carleton	AM-E	McKee, B.T.A.	10 000	Improvements to single photon emission computed tomography.
		Total grants:	25 000	
Concordia	FD-T	Harnad, J.	27 000	Integrable systems and gauge theory.
Concordia	MP-T	Ali, S.T.	16 000	Square integrable group representations: applications to quantization and signal analysis.
Concordia	MP-T	Hall, R.L.	14 000	Spectral geometry.
		Total grants:	57 000	
Ecole Poly.	OP-E	Bertrand, L.G.	20 000	Controles non destructifs par methodes optiques.
Ecole Poly.	OP-E	Gagné, J.M.	38 000	a) Etude des spectres optogalvaniques associés aux exctitations multiphotoniques par laser des atomes: U, Th, Zr, Gd, Fe et des gaz rares b) interaction laser-matiére.
Ecole Poly.	OP-E	Lacroix, S.	22 000	Effets non-linéaires de type Kerr dans les fibres effilées.

Table 34: (GSC-29 by institution, continued)

Ecole Poly.	OP-E	Najafi, S.I.	28 000	Functional integrated optics devices.
Ecole Poly.	PL-E	Bures, J.	20 000	Composants passifs tout-fibre: coupleurs séparateurs de modes et coupleurs polis et fusionnés.
		Total grants:	128 000	
Guelph	AM-E	Brooks, R.L.	32 000	Spectroscopy of simple molecules at cryogenic temperatures (group).
Guelph	AM-E	Gray, C.G.	35 000	Infrared, Raman and neutron spectra of C60 complexes. Theory and computer simulation studies of molecular fluids.
Guelph	AM-E	Hunt, J.L.	group	Charge-induced spectroscopy of solid hydrogens.
		Total grants:	67 000	
INRS	AM-E	Gregory, B.C.	group	Characterisation d'un faisceau diagnostique d'atoms légèrs et études spectroscopique.
INRS	AM-E	Ross, G.G.	27 700	Etude des interactions ions-matériaux et application á la modification des propriétiés des surface.
INRS	LA-E	Beaudoin, Y.	group	Sub-picosecond laser development and ultra-short X-ray generation.
INRS	LA-E	Kieffer, J.	group	Improvements of a high power peak power laser system.
INRS	PL-E	Chaker, M.	195 000	Laser-plasma interaction, X-ray lithography, and plasma processing studies (group).
INRS	PL-E	Paynter, R.	group	Surface modification by RF plasmas.
INRS	PL-E	Pepin, H.	group	Etude de faisabilité du déplacement contrôlé de la foudre par laser.
INRS	PL-E	Sarkissian, A.H.	group	Plasma source and energetic beam development for hot plasma and material research.
INRS	PL-E	Stansfield, B.L.	group	Particle transport in plasmas.
INRS	PL-E	Terreault, B.	129 500	Plasma and fusion research (group).
INRS	PL-T	Johnston, T.W.	group	Inertial confinement fusion simulations with sub-picosecond and nanosecond laser pulses.
INRS	PL-T	Marchand, R.	14 000	Finite element modelling of tolamak edge plasma.
		Total grants:	366 200	
Laval	AM-E	Baril, M.	13 900	Application de l'optique corpusculaire et de la spectrométrie de masse á la solution de problémes analytique et environnementaux.
Laval	AM-E	Chin, S.L.	47 000	High laser field physics.
Laval	AM-E	Knystautas, E.J.	52 000	Spectrscopie atomique a l'aide a'accelerateurs d'ions; implantation ionique.
Laval	AM-E	Larzillière, M.	35 000	Spectroscopie laser sur faisceaux d'ions rapides.
Laval	AM-E	Roy, D.	33 300	Spectrométrie électronique appliqée a l'etude des gaz et des surfaces.
Laval	AM-T	Dubé, L.J.	17 000	Collisional dynamics in ion-atom, ion-solid interactions.
Laval	AM-T	Tremblay, P.	18 000	Interaction entre un laser fluctuant en phase et un systeme atomique.
Laval	OP-E	Arsenault, H.H.	40 000	Optical and digital information processing.
Laval	OP-E	Bélanger, P.A.	55 000	Lasers et optique nonlinéaires appliqués.
Laval	OP-E	Denariez-Roberge,	15 000	Optique nonlinéaire des materiaux.
Laval	OP-E	Galstian, T.	32 000	Development de nouveaux matériaux et systemes optoélectronique pour le traitement de l'information.

Table 34: (GSC-29 by institution, continued)

Laval	OP-E	Lessard, R.A.	30 000	Holography and optical materials for photonic applications.
Laval	OP-E	McCarthy, N.	26 000	Physique des lasers destines au pompage optique.
Laval	OP-E	Piché, M.	60 000	Impulsions femtosecondes/attosecondes et structures périodiques.
Laval	OP-E	Sheng, Y.	26 000	Optical pattern recognition and optical computing.
Laval	OP-E	Tremblay, R.	17 500	Optique quidée et resonateur laser.
Laval	OP-E	Vallée, R.	30 000	La fibre comme milieu actif.
Laval	OP-E	Villeneuve, A.	30 000	Nonlinear guided wave phenomena in semiconductor waveguide at half bandgap.
		Total grants:	577 700	
Lethbridge	FD-T	Ali, M.K.	12 000	Chaos and classical-quantum correspondence.
Lethbridge	FD-T	Walton, M.A.	16 600	Conformal field theory and related systems.
Lethbridge	AM-E	Moazzen-Ahmadi, N.	27 000	High resolution infrared spectroscopy of transient molecules.
		Total grants:	55 600	
Manitoba	FD-T	Osborn, T.A.	16 600	Semiclassical quantum theory.
Manitoba	AM-E	Ens, E.W.	16 600	Fundamental processes in desorption time-of-flight mass spectroscopy of large molecules and clusters.
Manitoba	AM-E	Tabisz, G.C.	40 000	Molecular interactions and dynamics in dense gases studied by optical spectroscopy.
Manitoba	AM-E	Zetner, P.W.	27 000	The study of electron impact on excited state metal atoms.
		Total grants:	100 200	
McGill	MP-T	Sharp, R.T.	15 000	Group methods in physics.
		Total grants:	15 000	
McMaster	FD-T	Goodings, D.A.	12 000	Nonlinear dynamics of clasical and quantum systems.
McMaster	AM-E	Cassidy, D.T.	39 000	Physics and applications of III-V lasers and materials.
McMaster	AM-E	Chang, J.	32 000	Energetic electron induced atmospheric plasma processes.
McMaster	AM-E	Haugen, H.K.	37 900	Optical studies of negative ions and selected solid state systems.
		Total grants:	120 900	
Memorial	AM-E	Reddy, S.P.	27 000	Molecular spectroscopy with infrared and optical methods.
Memorial	AM-T	Gien, T.T.	18 000	Atomic and molecular scatterings.
		Total grants:	45 000	
Montréal	FD-T	Saint-Aubin, Y.	14 800	Individual models and critical phenomena.
Montréal	MP-T	Hussin, V.	14 800	Modeles supersymetriques en theories cassique et quantique et supergroupes.
Montréal	MP-T	Patera, J.	45 000	Aperiodic long range order and other symmetries in physics.
Montréal	MP-T	Vinet, L.	39 000	Symmetries in physics.
Montréal	MP-T	Winternitz, P.	45 000	Group theory and nonlinear phenomena in physics.

Table 34: (GSC-29 by institution, continued)

Montréal	PL-E	Margot, J.	27 000	Experimental and theoretical study of high-frequency-sustained magnetoplasmas and their optimization for application.
Montréal	PL-E	Moisan, M.	55 000	Decharges dans gaz moyen de champs électriques périodiques de haute fréquence: études fondamentales et applications.
		Total grants:	240 600	
UNB	AM-E	Lees, R.M.	46 000	Infrared and microwave spectroscopic and collisional energy transfer studies.
UNB	AM-E	Linton, C.	40 000	Laser spectroscopy of small molecules.
UNB	AM-E	Xu, L.	29 000	Eigenstate-resolved spectroscopy: a probe for vibrational mode coupling arising from internal rotation and inversion.
UNB	AM-T	Ross, S.C.	17 000	Multichannel quantum defect theory of hydrogen: large amplitude vibration of molecules.
UNB	OP-E	Bao, X.	32 000	Dynamic studies of Brillouin scattering process and its application to optical fibre based distributed sensors.
		Total grants:	164 000	
Ottawa	FD-T	Varshni, Y.P.	10 000	Investigations in theoretical physics.
Ottawa	MP-T	Hodgson, R.J.W.	8 000	Theoretical investigations of inverse problems.
Ottawa	MP-T	L'Heureux, I.	16 000	Non-quilibrium processes in nonlinear systems.
Ottawa	AM-E	Marmet, P.	24 000	Spectroscopie par impact electronique.
		Total grants:	58 000	
Hull	OP-T	Fontaine, M.	15 000	Propagation en régime lineaire et nonlinéaire dans las dispostifs optiques biréfringents.
		Total grants:	15 000	
Trois-Riv.	MP-T	Grundland, A.M.	16 000	The methods of symmetry reduction and Riemann invariants for nonlinear phenomena in physics.
		Total grants:	16 000	
Regina	MP-T	Papini, G.A.	8 300	Geometrical phases, theory and applications.
		Total grants:	8 300	
Sask.	MP-T	Soteros, C.E.	16 000	Lattice models of statistical physics: lattice animal models of branched polymers.
Sask.	PL-E	Conway, G.D.	group	Cross polarization scattering diagnostic for the measurement of magnetic fusion plasmas.
Sask.	PL-E	Hirose, A.	135 000	Plasma heating and anomalous transport in STOR-M Tokamak and double plasma device (group).
Sask.	PL-E	Xiao, C.	15 000	Clarification of Ohmic H-Mode induced by current pulse, external biasing and and CT injection in the STOR-M Tokamak.
Sask.	PL-T	Smolyakov, A.I.	22 000	Nonlinear processes in magnetized plasmas.
		Total grants:	188 000	

Table 34: (GSC-29 by institution, continued)

Sherbrooke	AM-E	Houde, D.	10 000	Study of phase transitions and charge transfer in solid probes by femtosecond time resolved non-degenerate four-wave mixing.
		Total grants:	10 000	
Simon Fraser	FD-T	Ballentine, L.E.	13 900	Quantum chaos and the quantum-classical interface.
Simon Fraser	OP-T	Enns, R.H.	22 000	Theoretical problems in nonlinear optics.
		Total grants:	35 900	
St. F. X.	AM-E	Joshi, Y.N.	38 000	Photo-emission and photo-absorption atmoic spectroscopy in vacuum UV region.
St. F. X.	AM-E	Wallbank, B.	26 800	Laser assisted electron atom collisions.
		Total grants:	64 800	
Toronto	AM-E	May, A.D.	35 000	Molecular spectroscopy and laser dynamics.
Toronto	AM-E	Stoicheff, B.P.	51 666	Laser physics and spectroscopy: quantum optics.
Toronto	LA-E	Herman, P.R.	25 900	Extreme-ultraviolet lasers for microfabrication of photonic devices.
Toronto	LA-E	Marjoribanks, R.S.	27 700	Atoms and plasmas in intense optical fields.
Toronto	OP-E	Mandelis, A.M.	32 400	Novel dynamic photothermal rate-window instrumentation and measurement techniques and applications.
Toronto	OP-E	Measures, R.M.	38 000	Active wavelength demodulation with well devices.
Toronto	OP-E	Smith, P.W.E.	41 600	Ultafast optics and photonics.
Toronto	PL-E	Pitcher, C.S.	9 000	Detached divertor studies in Tokamak de Varennes.
Toronto	PL-E	Stangeby, P.C.	40 000	Fusion energy: tokamak edge studies.
		Total grants:	301 266	
Victoria	AM-T	Poll, J.D.	15 000	Spectroscopy of intermolecular interactions.
		Total grants:	15 000	
Waterloo	AM-T	Chidichimo, M.C.	14 000	Excitation and ionization of positive ions by electron and proton impact.
Waterloo	AM-T	Liu, W.K.	25 000	Multiphoton excitation and molecular collision dynamics.
		Total grants:	39 000	
Western	AM-E	Holt, R.A.	27 700	Atomic and molecular structure and lifetime studies.
Western	AM-E	Mitchell, J.B.A.	37 000	Studies of electron-molecular ion collisons.
Western	AM-E	Rosner, S.D.	31 000	Atomic and molecular structure and lifetime studies.
Western	AM-T	Goldman, S.P.	27 700	Modified configuration interaction, relativistic and electrodynamic calculations in atomic physics.
Western	AM-T	Luke, T.M.	10 000	Structure and transitions in complex ions.
Western	AM-T	Talman, J.D.	9 000	Theoretical and computational methods for atomic and molecular systems.
		Total grants:	142 400	

Table 34: (GSC-29 by institution, continued)

W. Laurier	OP-E	Lit, J.W.Y.	38 000	Fibre optics.
W. Laurier	OP-T	Wartak, M.S.	15 000	Gain and linewidth enhancement factor in quantum well lasers.
		Total grants:	53 000	
Windsor	FD-T	Baylis, W.E.	36 000	Theory of atomic interactions.
Windsor	AM-E	Atkinson, J.B.	16 600	Laser induced fluorescence studies of molecules and clusters.
Windsor	AM-E	Czajkowski, M.A.	12 000	High res. laser spectrscopy of small molecules and atomic-molecular collision processes and interaction.
Windsor	AM-E	Jensen, E.T.	25 000	Dynamics and spectroscopy of dissociative states of molecules on surfaces.
Windsor	AM-E	Krause, L.	22 200	Atomic and molecular interactions.
Windsor	AM-E	McConkey, J.W.	85 000	Investigation of electron and photon collision phenomena in atoms and molecules.
Windsor	AM-E	Schlesinger, M.	18 000	Physical properties of artificially layered structure.
Windsor	AM-E	Van Wijngaarden, A	32 000	Lamb shift and radiative processes in precense of fields.
Windsor	AM-T	Drake, G.W.F.	63 000	Theory of atomic processes and structure.
Windsor	AM-T	Kent, R.D.	12 000	Unitary group approach and its applications.
		Total grants:	321 800	
York	FD-T	Darewych, J.W.G.	12 000	Few-particle theory.
York	AM-E	Carswell, A.I.	29 600	Laser diagnostics of the atmosphere.
York	AM-E	Hessels, E.A.	27 700	Precision studies of Rydberg states of few electron atoms.
York	AM-E	van Wijngaarden, W	27 700	Laser spectroscopy of atoms.
York	AM-T	Horbatsch, M.	33 000	Many body problem in scattering and field theory.
York	AM-T	McEachran, R.P.	37 000	Theoretical and computation studies of atomic collisions and structure (group).
York	AM-T	Stauffer, A.D.	group	Theoretical and computational studies of atomic collisions and structure.
York	OP-T	Freedhoff, H.S.	15 000	Theoretical studies in quantum optics involving multilevel, multi-atom and multiphoton transitions.
		Total grants:	182 000	

Table 35: Research programs funded by GSC-29, ordered by field.

Field	Name	University	Amount	Description
FD-T	Tuszynski, J.A.	Alberta	15 000	Nonperturbative field theory and self organization.
FD-T	Ahlborn, B.	UBC	10 000	Vortex Dynamics.
FD-T	Harnad, J.	Concordia	27 000	Integrable systems and gauge theory.
FD-T	Ali, M.K.	Lethbridge	12 000	Chaos and classical-quantum correspondence.
FD-T	Walton, M.A.	Lethbridge	16 600	Conformal field theory and related systems.
FD-T	Osborn, T.A.	Manitoba	16 600	Semiclassical quantum theory.
FD-T	Goodings, D.A.	McMaster	12 000	Nonlinear dynamics of clasical and quantum systems.
FD-T	Saint-Aubin, Y.	Montréal	14 800	Individual models and critical phenomena.
FD-T	Varshni, Y.P.	Ottawa	10 000	Investigations in theoretical physics.
FD-T	Ballentine, L.E.	Simon Fraser	13 900	Quantum chaos and the quantum-classical interface.
FD-T	Baylis, W.E.	Windsor	36 000	Theory of atomic interactions.
FD-T	Darewych, J.W.G.	York	12 000	Few-particle theory.
		Total grants:	195 900	
MP-T	Ali, S.T.	Concordia	16 000	Square integrable group representations: applications to quantization and signal analysis.
MP-T	Hall, R.L.	Concordia	14 000	Spectral geometry.
MP-T	Sharp, R.T.	McGill	15 000	Group methods in physics.
MP-T	Hussin, V.	Montréal	14 800	Modeles supersymetriques en theories cassique et quantique et supergroupes.
MP-T	Patera, J.	Montréal	45 000	Aperiodic long range order and other symmetries in physics.
MP-T	Vinet, L.	Montréal	39 000	Symmetries in physics.
MP-T	Winternitz, P.	Montréal	45 000	Group theory and nonlinear phenomena in physics.
MP-T	Hodgson, R.J.W.	Ottawa	8 000	Theoretical investigations of inverse problems.
MP-T	L'Heureux, I.	Ottawa	16 000	Non-quilibrium processes in nonlinear systems.
MP-T	Grundland, A.M.	Trois-Riv.	16 000	The methods of symmetry reduction and Riemann invariants for nonlinear phenomena in physics.
MP-T	Papini, G.A.	Regina	8 300	Geometrical phases, theory and applications.
MP-T	Soteros, C.E.	Sask.	16 000	Lattice models of statistical physics: lattice animal models of branched polymers.
		Total grants:	253 100	
AM-E	Pinnington, E.H.	Alberta	50 000	Atomic physics using fast ion beams (group).
AM-E	Smy, P.R.	Alberta	20 000	Combustion physics.
AM-E	Auerbach, D.E.	UBC	26 000	Chaotic dynamics, control and correlations in spatially extended systems.
AM-E	Balzarini, D.A.	UBC	10 000	Optical studies of phase transitions in pure fluids, binary fluids and liquid crystals and electron momentum spectroscopy.
AM-E	Ozier, I.	UBC	42 000	High resolution molecular spectroscopy: magnetic rotation, ions, and large amplitude motion.
AM-E	Johns, P.C.	Carleton	15 000	Medical X-ray imaging physics research program.
AM-E	McKee, B.T.A.	Carleton	10 000	Improvements to single photon emission computed tomography.
AM-E	Brooks, R.L.	Guelph	32 000	Spectroscopy of simple molecules at cryogenic temperatures (group).

Table 35: (GSC-29 by field, continued)

AM-E	Gray, C.G.	Guelph	35 000	Infrared, Raman and neutron spectra of C60 complexes. Theory and computer simulation studies of molecular fluids.
AM-E	Hunt, J.L.	Guelph	group	Charge-induced spectroscopy of solid hydrogens.
AM-E	Gregory, B.C.	INRS	group	Characterisation d'un faisceau diagnostique d'atoms légèrs et études spectroscopique.
AM-E	Ross, G.G.	INRS	27 700	Etude des interactions ions-matériaux et application á la modification des propriétiés des surface.
AM-E	Baril, M.	Laval	13 900	Application de l'optique corpusculaire et de la spectrométrie de masse á la solution de problémes analytique et environnementaux.
AM-E	Chin, S.L.	Laval	47 000	High laser field physics.
AM-E	Knystautas, E.J.	Laval	52 000	Spectrscopie atomique a l'aide a'accelerateurs d'ions; implantation ionique.
AM-E	Larzillière, M.	Laval	35 000	Spectroscopie laser sur faisceaux d'ions rapides.
AM-E	Roy, D.	Laval	33 300	Spectrométrie électronique appliqée a l'etude des gaz et des surfaces.
AM-E	Moazzen-Ahmadi, N.	Lethbridge	27 000	High resolution infrared spectroscopy of transient molecules.
AM-E	Ens, E.W.	Manitoba	16 600	Fundamental processes in desorption time-of-flight mass spectroscopy of large molecules and clusters.
AM-E	Tabisz, G.C.	Manitoba	40 000	Molecular interactions and dynamics in dense gases studied by optical spectroscopy.
AM-E	Zetner, P.W.	Manitoba	27 000	The study of electron impact on excited state metal atoms.
AM-E	Cassidy, D.T.	McMaster	39 000	Physics and applications of III-V lasers and materials.
AM-E	Chang, J.	McMaster	32 000	Energetic electron induced atmospheric plasma processes.
AM-E	Haugen, H.K.	McMaster	37 900	Optical studies of negative ions and selected solid state systems.
AM-E	Reddy, S.P.	Memorial	27 000	Molecular spectroscopy with infrared and optical methods.
AM-E	Lees, R.M.	UNB	46 000	Infrared and microwave spectroscopic and collisional energy transfer studies.
AM-E	Linton, C.	UNB	40 000	Laser spectroscopy of small molecules.
AM-E	Xu, L.	UNB	29 000	Eigenstate-resolved spectroscopy: a probe for vibrational mode coupling arising from internal rotation and inversion.
AM-E	Marmet, P.	Ottawa	24 000	Spectroscopie par impact electronique.
AM-E	Houde, D.	Sherbrooke	10 000	Study of phase transitions and charge transfer in solid probes by femtosecond time resolved non-degenerate four-wave mixing.
AM-E	Joshi, Y.N.	St. F. X.	38 000	Photo-emission and photo-absorption atmoic spectroscopy in vacuum UV region.
AM-E	Wallbank, B.	St. F. X.	26 800	Laser assisted electron atom collisions.
AM-E	May, A.D.	Toronto	35 000	Molecular spectroscopy and laser dynamics.
AM-E	Stoicheff, B.P.	Toronto	51 666	Laser physics and spectroscopy: quantum optics.
AM-E	Holt, R.A.	Western	27 700	Atomic and molecular structure and lifetime studies.

Table 35: (GSC-29 by field, continued)

AM-E	Mitchell, J.B.A.	Western	37 000	Studies of electron-molecular ion collisons.
AM-E	Rosner, S.D.	Western	31 000	Atomic and molecular structure and lifetime studies.
AM-E	Atkinson, J.B.	Windsor	16 600	Laser induced fluorescence studies of molecules and clusters.
AM-E	Czajkowski, M.A.	Windsor	12 000	High resolution laser spectrscopy of small molecules and atomic- molecular collision processes and interaction.
AM-E	Jensen, E.T.	Windsor	25 000	Dynamics and spectroscopy of dissociative states of molecules on surfaces.
AM-E	Krause, L.	Windsor	22 200	Atomic and molecular interactions.
AM-E	McConkey, J.W.	Windsor	85 000	Investigation of electron and photon collision phenomena in atoms and molecules.
AM-E	Schlesinger, M.	Windsor	18 000	Physical properties of artificially layered structure.
AM-E	Van Wijngaarden, A	Windsor	32 000	Lamb shift and radiative processes in precense of fields.
AM-E	Carswell, A.I.	York	29 600	Laser diagnostics of the atmosphere.
AM-E	Hessels, E.A.	York	27 700	Precision studies of Rydberg states of few electron atoms.
AM-E	van Wijngaarden, W	York	27 700	Laser spectroscopy of atoms.
		Total grants:	1 387 366	
AM-T	Razavy, M.	Alberta	12 000	Multi-dimensional quantum tunneling with and without dissapative coupling.
AM-T	Spanos, T.J.T.	Alberta	7 000	Physics of megascopic mixtures and macromolecular systems.
AM-T	Stephenson, J.	Alberta	6 000	Modelling in non-linear dynamics and statistical mechanics.
AM-T	Dubé, L.J.	Laval	17 000	Collisional dynamics in ion-atom, ion-solid interactions.
AM-T	Tremblay, P.	Laval	18 000	Interaction entre un laser fluctuant en phase et un systeme atomique.
AM-T	Gien, T.T.	Memorial	18 000	Atomic and molecular scatterings.
AM-T	Ross, S.C.	UNB	17 000	Multichannel quantum defect theory of hydrogen: large amplitude vibration of molecules.
AM-T	Poll, J.D.	Victoria	15 000	Spectroscopy of intermolecular interactions.
AM-T	Chidichimo, M.C.	Waterloo	14 000	Excitation and ionization of positive ions by electron and proton impact.
AM-T	Liu, W.K.	Waterloo	25 000	Multiphoton excitation and molecular collision dynamics.
AM-T	Goldman, S.P.	Western	27 700	Modified configuration interaction, relativistic and electrodynamic calculations in atomic physics.
AM-T	Luke, T.M.	Western	10 000	Structure and transitions in complex ions.
AM-T	Talman, J.D.	Western	9 000	Theoretical and computational methods for atomic and molecular systems.
AM-T	Drake, G.W.F.	Windsor	63 000	Theory of atomic processes and structure.
AM-T	Kent, R.D.	Windsor	12 000	Unitary group approach and its applications.
AM-T	Horbatsch, M.	York	33 000	Many body problem in scattering and field theory.
AM-T	McEachran, R.P.	York	37 000	Theoretical and computation studies of atomic collisions and structure (group).
AM-T	Stauffer, A.D.	York	group	Theoretical and computational studies of atomic collisions and structure.
		Total grants:	340 700	

Table 35: (GSC-29 by field, continued)

LA-E	Beaudoin, Y.	INRS	group	Sub-picosecond laser development and ultra-short X-ray generation.
LA-E	Kieffer, J.	INRS	group	Improvements of a high power peak power laser system.
LA-E	Herman, P.R.	Toronto	25 900	Extreme-ultraviolet lasers for microfabrication of photonic devices.
LA-E	Marjoribanks, R.S.	Toronto	27 700	Atoms and plasmas in intense optical fields.
		Total grants:	53 600	
OP-E	Bertrand, L.G.	Ecole Poly.	20 000	Controles non destructifs par methodes optiques.
OP-E	Gagné, J.M.	Ecole Poly.	38 000	a) Etude des spectres optogalvaniques associés aux exctitations multiphotoniques par laser des atomes: U, Th, Zr, Gd, Fe et des gaz rares b) interaction laser-matiére.
OP-E	Lacroix, S.	Ecole Poly.	22 000	Effets non-linéaires de type Kerr dans les fibres effilées.
OP-E	Najafi, S.I.	Ecole Poly.	28 000	Functional integrated optics devices.
OP-E	Arsenault, H.H.	Laval	40 000	Optical and digital information processing.
OP-E	Bélanger, P.A.	Laval	55 000	Lasers et optique nonlinéaires appliqués.
OP-E	Denariez-Roberge,	Laval	15 000	Optique nonlinéaire des materiaux.
OP-E	Galstian, T.	Laval	32 000	Development de nouveaux matériaux et systemes optoélectronique pour le traitement de l'information.
OP-E	Lessard, R.A.	Laval	30 000	Holography and optical materials for photonic applications.
OP-E	McCarthy, N.	Laval	26 000	Physique des lasers destines au pompage optique.
OP-E	Piché, M.	Laval	60 000	Impulsions femtosecondes/attosecondes et structures périodiques.
OP-E	Sheng, Y.	Laval	26 000	Optical pattern recognition and optical computing.
OP-E	Tremblay, R.	Laval	17 500	Optique quidée et resonateur laser.
OP-E	Vallée, R.	Laval	30 000	La fibre comme milieu actif.
OP-E	Villeneuve, A.	Laval	30 000	Nonlinear guided wave phenomena in semiconductor waveguide at half bandgap.
OP-E	Bao, X.	UNB	32 000	Dynamic studies of Brillouin scattering process and its application to optical fibre based distributed sensors.
OP-E	Mandelis, A.M.	Toronto	32 400	Novel dynamic photothermal rate-window instrumentation and measurement techniques and applications.
OP-E	Measures, R.M.	Toronto	38 000	Active wavelength demodulation with well devices.
OP-E	Smith, P.W.E.	Toronto	41 600	Ultafast optics and photonics.
OP-E	Lit, J.W.Y.	W. Laurier	38 000	Fibre optics.
		Total grants:	651 500	
OP-T	Fontaine, M.	Hull	15 000	Propagation en régime lineaire et nonlinéaire dans las dispostifs optiques biréfringents.
OP-T	Enns, R.H.	Simon Fraser	22 000	Theoretical problems in nonlinear optics.
OP-E	Wartak, M.S.	W. Laurier	15 000	Gain and linewidth enhancement factor in quantum well lasers.

Table 35: (GSC-29 by field, continued)

OP-T	Freedhoff, H.S.	York	15 000	Theoretical studies in quantum optics involving multilevel, multi-atom and multiphoton transitions.
		Total grants:	67 000	
PL-E	MacLatchy, C.S.	Acadia	7 000	Applications of lagmuir probes in plasma diagnostics.
PL-E	Fedosejevs, R.	Alberta	48 000	High intensity picosecond and femtosecond UV laser-plasma interactions.
PL-E	Offenberger, A.A.	Alberta	70 000	High field physics.
PL-E	Meyer, J.	UBC	46 200	Laser plasma interactions and ultrashort pulse laser physics.
PL-E	Ng, A.	UBC	58 000	Physics at high energy density.
PL-E	Bures, J.	Ecole Poly.	20 000	Composants passifs tout-fibre: coupleurs séparateurs de modes et coupleurs polis et fusionnés.
PL-E	Chaker, M.	INRS	195 000	Laser-plasma interaction, X-ray lithography, and plasma processing studies (group).
PL-E	Paynter, R.	INRS	group	Surface modification by RF plasmas.
PL-E	Pepin, H.	INRS	group	Etude de faisabilité du déplacement contrôlé de la foudre par laser.
PL-E	Sarkissian, A.H.	INRS	group	Plasma source and energetic beam development for hot plasma and material research.
PL-E	Stansfield, B.L.	INRS	group	Particle transport in plasmas.
PL-E	Terreault, B.	INRS	129 500	Plasma and fusion research (group).
PL-E	Margot, J.	Montréal	27 000	Experimental and theoretical study of high-frequency-sustained magnetoplasmas and their optimization for application.
PL-E	Moisan, M.	Montréal	55 000	Decharges dans gaz moyen de champs électriques périodiques de haute fréquence: études fondamentales et applications.
PL-E	Conway, G.D.	Sask.	group	Cross polarization scattering diagnostic for the measurement of magnetic fusion plasmas.
PL-E	Hirose, A.	Sask.	135 000	Plasma heating and anomalous transport in STOR-M Tokamak and double plasma device (group).
PL-E	Xiao, C.	Sask.	15 000	Clarification of Ohmic H-Mode induced by current pulse, external biasing and and CT injection in the STOR-M Tokamak.
PL-E	Pitcher, C.S.	Toronto	9 000	Detached divertor studies in Tokamak de Varennes.
PL-E	Stangeby, P.C.	Toronto	40 000	Fusion energy: tokamak edge studies.
		Total grants:	854 700	
PL-T	Capjack, C.E.	Alberta	25 000	Simulation of laser plasma interactions.
PL-T	Rozmus, W.	Alberta	30 500	Theoretical plasma physics–Laser plasma interactions.
PL-T	Johnston, T.W.	INRS	group	Inertial confinement fusion simulations with sub-picosecond and nanosecond laser pulses.
PL-T	Marchand, R.	INRS	14 000	Finite element modelling of tolamak edge plasma.
PL-T	Smolyakov, A.I.	Sask.	22 000	Nonlinear processes in magnetized plasmas.
		Total grants:	91 500	

D Tabular Summaries of Research Programs for GSC-17

The following tables summarize the research programs funded by GSC-17, ordered by institution (Table 36), and by field of study (Table 37). The various subfields are defined as follows:

- AP – Astrophysics, with AP-G denoting studies of galactic structure and evolution, and AP-S denoting studies of stellar structure and evolution.
- AT – Atmospheric physics, including both theoretical (AT-T) and experimental (AT-E) studies.
- OB – Observational astronomy.
- PS – Planetary physics and space science.
- GR – General relativity and gravitation, with the subfields Cosmology (GR-C), Mathematical Relativity (GR-M), Numerical Relativity (GR-N), Particle Physics (GR-P), and Quantum Gravity (GR-Q).

Table 36: Research programs funded by GSC-17, ordered by institution.

University	Field	Name	Amount	Description
Alberta	GR-M	Israel, W.	65 000	Strong gravitational fields.
Alberta	GR-M	Kunzle, H.P.	15 000	Solutions of Einstein-Yang-Mills equations.
Alberta	GR-Q	Frolov, V.	60 000	Quantum gravity and black hole physics.
Alberta	GR-Q	Page, D.N.	55 000	Quantum gravity, black holes, and cosmology.
Alberta	AT-T	Rankin, R.	20 000	Nonlinear magnetohydrodynamic processes in auroral structures.
Alberta	AT-T	Rostoker, G.	80 000	The physics of the solar-terrestrial interaction.
Alberta	AT-T	Samson, J.C.	50 000	Magnetohydrodynamic waves and substorms.
Alberta	OB-E	Hube, D.P.	9 000	Observational studies of binary and variable stars, and of supernova remnants.
Alberta	OB-E	Landbecker, T.L.	18 000	Radio astronomy instrumentation and interstellar medium research.
Alberta	OB-E	Routledge,D.	10 000	Instrumentation for radio astronomy, and interstellar medium research.
Alberta	OB-E	Vaneldik, J.F.	18 000	Radio astronomy receiving systems supernova renmants.
		Total grants:	400 000	
Bishops	AP-S	Nelson, L.A.	17 500	Theoretical investigations of very low-mass stars and binaries containing compact objects.
		Total grants:	17 500	
Brandon	OB-E	Gulliver, A.F.	9 000	High dispersion spectroscopy of early-type stars.
Brandon	OB-E	Rice, J.B.	15 000	Doppler imaging of the surfaces of active stars.
		Total grants:	24 000	
UBC	GR-C	Halpern, M.	65 000	Measurement of the anisotopy of cosmic microwave background using a stratospheric telescope.
UBC	GR-C	Scott, D.	25 000	Theoretical studies of cosmic microwave background anisotropies.
UBC	GR-M	Schleich, K.	21 000	Topology and dynamics in classical and quantum cosmolgy.
UBC	GR-Q	Unruh, W.G.	80 000	Quantum mechanics and gravity.
UBC	AP-G	Gregory, P.C.	15 000	Cosmic jets and bayesian inference in astrophysics.
UBC	AP-G	Menon, T.K.	5 000	Cosmological evolution of radio sources.
UBC	AP-S	Matthews, J.M.	25 000	Pulsating stars as diagnostic tools in astrophysics.
UBC	AP-S	Richer, H.B.	47 000	Star and cluster formation in the early universe.
UBC	OB-E	Fahlman, G.G.	47 000	Photometric and spectroscopic studies of stars and stellar systems.
UBC	OB-E	Hickson, P.	40 000	Cosmology with large liquid mirror telescopes.
UBC	OB-E	Underhill, A.B.	14 000	Spectra of o and wolf-rayet stars.
UBC	OB-E	Walker, G.A.H.	60 000	Stellar astronomy.
		Total grants:	444 000	

Table 36: (GSC-17 by institution, continued)

Calgary	GR-N	Hobill, D.W.	33 000	Computational relativity and gravitation.
Calgary	AP-S	Kwok, S.	50 000	Effects of mass loss on the late stages of stellar evolution.
Calgary	AP-S	Milone, E.F.	21 000	Variable stars as tracers of stellar evolution.
Calgary	AP-S	Venkatesan, D.	10 000	Space physics and astronomy.
Calgary	AP-T	Leahy, D.A.	25 000	High energy phenomena in astrophysics.
Calgary	AT-E	Cogger, L.L.	53 000	Investigation of the Earth's aurora by means of UV imagers on orbiting satellites.
Calgary	AT-E	Knudsen, D.	23 000	Auroral particle acceleration at subkilometer scales.
Calgary	AT-E	Murphree, J.S.	60 000	Usage of auroral images for magnetospheric study.
Calgary	AT-E	Yau, A.	25 000	Polar ionospheric energization and transport.
Calgary	AT-T	Hearn, D.J.	12 000	The relation between the auroral distribution and magnetospheric processes.
Calgary	OB-E	Clark, T.A.	6 000	Infrared and submillimeter spectroscopic studies of the solar photosphere and chromosphere.
Calgary	OB-E	Taylor, A.R.	50 000	Radio astrophysics of stars and related galactic phenomena.
		Total grants:	368 000	
Dalhousie	GR-M	Coley, A.A.	22 000	Exact and qualitative of cosmological models.
		Total grants:	22 000	
Guelph	GR-N	Poisson, E.	30 000	Gravitational-wave generation and radiation reaction in compact binary systems.
		Total grants:	30 000	
Laval	AP-G	Hardy, E.J.	30 000	Internal structure and evolution of galaxies and of the galactic neighbourhood.
Laval	AP-G	Joncas, G.	27 000	Etude cinematique et dynamique de complexes gazeux galactiques.
Laval	AP-G	Roy, J.R.	35 000	Evolution des galaxies riches en gaz.
Laval	AP-S	Pineault, S.	12 000	Supernova remnants and stellar winds in the interstellar medium, and compact objects.
Laval	OB-E	Borra, E.F.	40 000	Liquid mirror telescopes.
		Total grants:	144 000	
Lethbridge	OB-E	Naylor, D.A.	33 000	Far IR spectroscopy of the atmospheres of giant planets.
		Total grants:	33 000	
McMaster	AP-S	Harris, W.E.	50 000	Old stellar systems in galaxies.
McMaster	AP-S	Pudritz, R.E	45 000	Formation of stars and globular cluster systems.
McMaster	AP-S	Welch, D.L.	35 000	Effects of metallicity on cepheid variable properties.
McMaster	AP-T	Sutherland, P.G.	25 000	Theoretical astrophysics: supernovae and smoothed particle hydrodynamics.
		Total grants:	155 000	
Memorial	AP-S	Forbes, D.W.	6 000	Star formation and evolution in young clusters and OB associations.
Memorial	AP-T	Summers, D.	30 000	Studies in theoretical space physics.
		Total grants:	36 000	
Montréal	AP-G	Carigran, C.	25 000	Distribution de masse dans les galaxies spirales et naines.
Montréal	AP-G	Demers, S.	25 000	Nearby dwarf galaxies.

Table 36: (GSC-17 by institution, continued)

Montréal	AP-S	Bastien, P.	30 000	Etudes theoriques et observationnelles de la formation des etoiles.
Montréal	AP-S	Fontaine, G.	105 000	Etudes des proprietes physiques des etoiles naines blanches (group).
Montréal	AP-S	Michaud, G.J.	60 000	Abondance des elements et hydrodynamique stellaire.
Montréal	AP-S	Wesemael, F.	group	Propriete atmospheriques des etoiles naines blanches et sous-naines.
Montréal	OB-E	Moffat, A.F.J.	55 000	Objects of high luminosity and structure of the galaxy.
Montréal	OB-E	Nadeau, D.	24 000	Astronomie infrarouge des regions de formation d'etoiles et des galaxies.
Montréal	OB-E	Racine, R.	46 000	Amas globularies et halos galactiques/imagerie haute resolution.
		Total grants:	370 000	
Mount Allison	PS-E	Hawkes, R.L.	8 000	Structure of cometary, asteroidal, and hyperbolic meteoroids.
		Total grants:	8 000	
UNB	GR-M	Tupper, B.O.J.	5 000	Spacetimes symmetries in general relativity.
UNB	GR-P	Gegenberg, J.D.	15 000	Quantum gravity and topological field theory.
UNB	AT-T	Hamza, A.M.	20 000	Plasma turbulence in auroral and solar physics.
UNB	AT-T	Timothy, J.G.	35 000	Physics of solar and stellar atmospheres and of solar-terrestrial relationships.
		Total grants:	75 000	
Queens	GR-C	Duncan, M.J.	35 000	Formation and dynamical evolution of astrophysical systems.
Queens	GR-C	Henriksen, R.N.	35 000	Protostellar outflow: N-body clusters; pulsar magnetoshperes; galactic structure and evolution.
Queens	GR-M	Lake, K.W.	18 000	Gravitation, relativistic astrophysics and cosmology.
Queens	GR-P	Widrow, L.M.	22 000	Dark matter and the large scale structure of the universe.
Queens	AP-G	Hanes, D.A.	20 000	Extragalactic globular cluster systems; the cosmic scale distance.
Queens	AP-G	Irwin, J.A.	23 000	Winds, jets, bubbles and fountains — a study of gas flows within and around galaxies.
Queens	AP-S	Hughes, V.A.	10 000	Star formation and the interstellar medium.
		Total grants:	163 000	
Regina	GR-M	Coleman, R.A.	8 000	The mathematical and philosophical foundations of the general theory of relativity and other spacetime theories (group).
Regina	AP-S	Bergbusch, P.A.	6 000	Luminosity and temperature functions for old stellar systems.
		Total grants:	14 000	
Saint Mary's	AP-G	West, M.J.	20 000	The formation of cD galaxies.
Saint Mary's	AP-S	Guenther, D.B.	15 000	Seismology of the sun and stars as a test of stellar structure and evolution.
Saint Mary's	AP-S	Mitchell, G.F.	47 000	Molecular clouds and star formation.
Saint Mary's	AP-S	Turner, D.G.	18 000	Open clusters and cepheid variables.
Saint Mary's	AP-T	Clarke, D.A.	21 000	Numerical simulations of astrophysical gas dynamics.
		Total grants:	121 000	

Table 36: (GSC-17 by institution, continued)

Sask.	AT-E	Davis, G.R.	30 000	Infrared spectroscopy of terrestrial and planetary atmospheres.
Sask.	AT-E	Koehler, J.A.R.	75 000	Coherent vhf cw doppler radar - polarimeter studies of radar aurora and foward scatter (group).
Sask.	AT-E	Koustov, A.	18 000	Multi-instrumental studies of the high-latitude ionospheric and magnetospheric processes.
Sask.	AT-E	Llewelyn, E.J.	50 000	Aeronomy of the terrestrial atmosphere.
Sask.	AT-E	Manson, A.H.	95 000	Dynamics of the middle atmosphere (60-110km) based on Saskatoon MF radars and collaborations with regional, glogal and satellite systems/networks.
Sask.	AT-E	McEwen, D.J.	30 000	Auroral processes.
Sask.	AT-E	Oznovich, I.	15 000	Airglow studies of the arctic upper mesosphere and lower thermosphere.
Sask.	AT-E	Steele, D.P.	10 000	Polar diffuse aurora and its magnetospheric implications.
		Total grants:	323 000	
Toronto	GR-C	Bond, J.R.	80 000	Cosmic structure theory in post COBE era.
Toronto	GR-C	Carlberg, R.G.	40 000	Galaxies and cosmology.
Toronto	GR-C	Kaiser, N.	98 900	Gravitational lensing and large scale structure.
Toronto	GR-C	Tremaine, S.D.	95 000	Studies of the solar system and galaxy dynamics.
Toronto	GR-M	Dyer, C.C.	25 000	Applications of general relativity to cosmology.
Toronto	AP-G	Lilly, S.J.	55 000	Galaxies at high redshifts.
Toronto	AP-G	Martin, P.G.	50 000	Inquires into the galactic ecosystem.
Toronto	AP-S	Bolton, C.T.	28 000	Fundamental properties and atmospheres of OB stars.
Toronto	AP-S	Clement, C.M.	9 000	Study of variable stars in globular clusters.
Toronto	AP-S	Clement, M.J.Y.	5 000	Equillibrium and stability of rapidly rotating stars.
Toronto	AP-S	Fernie, J.D.	21 000	Variable star research.
Toronto	AP-S	Murray, N.W.	25 000	Applications of dynamics in the solar system and active galactic nuclei.
Toronto	AP-S	Percy, J.R.	19 000	Studies of variable stars.
Toronto	OB-E	Garrison, R.F.	26 000	Classification of stellar spectra.
Toronto	OB-E	Kronberg, P.P.	70 000	Observation-based studies of galaxies, quasars, cosmic magnetic fields, and the starburst phenomenon.
Toronto	OB-E	Lester, J.B.	20 000	Quantitative spectroscopic studies of the atmosphere of luminous cool stars.
Toronto	OB-E	Mochnacki, S.W.	9 000	Mapping the photoshperes of close binary stars.
Toronto	OB-E	Seaquist, E.R.	75 000	Radio studies of circumstellar envelopes and extragalactic star formation.
Toronto	OB-E	Yee, H.K.C.	50 000	The CNOC redshift surveys: the universe at intermediate redshift.
		Total grants:	800 900	

Table 36: (GSC-17 by institution, continued)

Trent	AP-G	Dawson, P.C.	14 000	Galactic structure and stellar populations.
		Total grants:	14 000	
Victoria	GR-M	Cooperstock, F.I.	10 000	Problems in general relativity and cosmology.
Victoria	AP-S	Hartwick, F.D.A.	35 000	Evolution of stars and galaxies.
Victoria	AP-S	Pritchet, C.J.	60 000	Structure and evolution of stellar systems.
Victoria	AP-S	Vandenburg, D.A.	65 000	Absolute/relative ages and mass functions of globular clusters.
Victoria	AT-T	Horita, R.E.	5 000	Theory of plasma waves and its application in space physics.
Victoria	OB-E	Gower, A.C.	11 000	Radio studies of quasars, radiogalaxies and galactic systems.
Victoria	OB-E	Richardson, E.H.	7 000	Optical designs of telescopes and spectrographs for earth and space.
Victoria	OB-E	Scarfe, C.D.	6 000	Studies of binary and multiple stars, and of open cluster evolution in the near infrared.
		Total grants:	199 000	
Waterloo	GR-C	Hewitt, C.G.	6 000	Evolution of spatially homogeneous and inhomogeneous cosmologies.
Waterloo	GR-C	Wainwright, J.	23 000	Einstein's equations and the evolution of cosmological models.
Waterloo	GR-C	Wesson, P.S.	12 000	Tests of particles and fields using spacecraft.
Waterloo	GR-M	McLenaghan, R.G.	20 000	General relativity and differential geometry.
Waterloo	GR-P	Mann, R.B.	36 000	Exploring gravity's foundations.
Waterloo	AP-G	Harris, G.L.H	12 000	Extragalactic globular cluster systems and galaxy halos.
Waterloo	AP-S	Duley, W.W.	75 000	Physics and chemistry of interstellar matter.
Waterloo	AP-S	Fich, M.	14 000	Star formation and the interstellar medium.
		Total grants:	198 000	
Western	GR-C	Couchman, H.M.P.	35 000	Formation of cosmic structure.
Western	GR-N	Mann, P.J.	10 000	Numerical models of gravitational collapse.
Western	AP-S	Gray, D.F.	65 000	Dynamics of stellar atmospheres.
Western	AP-S	Landstreet, J.D.	55 000	Magnetic fields/chemical abundances/velocity fields in main sequence A/B stars.
Western	AP-S	Marlborough, J.M.	27 000	Kinematical and dynamical structure of the circumstellar matter around hot stars.
Western	AP-S	Mitalas, R.	5 000	Stellar structure and evolution.
Western	AT-E	Lowe, R.P.	15 000	Optical characterization of middle atmosphere gravity waves.
Western	AT-E	MacDougall, J.W.	10 000	Ionospheric studies using radars.
Western	AT-E	Sica, R.J.	35 000	High temporal-spatial resolution measurements of atmospheric coupling.
Western	AT-E	St. Maurice, J.P.	50 000	Small scale processes in auroral physics.
Western	AT-T	Hocking, W.K.	45 000	Coupling of wave motions and turbulence in the earth's middle atmosphere.
Western	AT-T	Moorcroft, D.R.	40 000	Studies of ionospheric structure.
Western	OB-E	Wehlau, A.F.	6 000	Studies of pulsating variable stars.
Western	PS-E	Jones, J.	18 000	Meteor studies.
Western	PS-E	Stooke, P.J.	5 000	Geological mapping of planetary surfaces.
		Total grants:	421 000	

Table 36: (GSC-17 by institution, continued)

Windsor	GR-M	Glass, E.N.	6 000	General relativity and relativistic astrophysics.
		Total grants:	6 000	
York	GR-C	Bartel, N.	40 000	Galactic and extragalactic compact radio sources.
York	AP-G	De Roberts, M.M.	30 000	Investigations of activity in galactic nuclei.
York	AP-G	McCall, M.L.	30 000	The chemistry of galaxies.
York	AP-S	Innanen, K.A.	30 000	Studies in galactic, stellar and planetary dynamics.
York	AP-S	Kingsburgh, R.L.	18 000	Study of abundances in stellar populations as a function of metallicity.
York	AP-S	Rucinski, S.M.	28 000	Formation and evolution of contact binary stars.
York	AT-E	Gault, W.A.	10 000	Optical measurements of upper atmosphere winds at Resolute Bay, NWT.
York	AT-E	McConnell, J.C.	35 000	Chemistry and dynamical interaction in planetary atmospheres.
York	AT-E	McDade, I.C.	18 000	Airglow mechanisms and atmospheric composition studies.
York	AT-E	Nicholls, R.W.	15 000	Space spectrscopy: maps, hires, photodissociation.
York	AT-E	Shepard, G.G.	65 000	Global dynamics of the mesosphere and thermosphere.
York	AT-T	Laframboise, J.G.	33 000	Theory of electrode devices in plasmas, and spacecraft-plasma interactions.
York	OB-E	Caldwell, J.J	30 000	Planetary studies with Hubble Space Telescope and with ground-based telescopes.
		Total grants:	382 000	

Table 37: Research programs funded by GSC-17, ordered by field.

Field	Name	University	Amount	Description
GR-C	Halpern, M.	UBC	65 000	Measurement of the anisotopy of cosmic microwave background using a stratospheric telescope.
GR-C	Scott, D.	UBC	25 000	Theoretical studies of cosmic microwave background anisotropies.
GR-C	Duncan, M.J.	Queens	35 000	Formation and dynamical evolution of astrophysical systems.
GR-C	Henriksen, R.N.	Queens	35 000	Protostellar outflow: N-body clusters; pulsar magnetoshperes; galactic structure and evolution.
GR-C	Bond, J.R.	Toronto	80 000	Cosmic structure theory in post COBE era.
GR-C	Carlberg, R.G.	Toronto	40 000	Galaxies and cosmology.
GR-C	Kaiser, N.	Toronto	98 900	Gravitational lensing and large scale structure.
GR-C	Tremaine, S.D.	Toronto	95 000	Studies of the solar system and galaxy dynamics.
GR-C	Hewitt, C.G.	Waterloo	6 000	Evolution of spatially homogeneous and inhomogeneous cosmologies.
GR-C	Wainwright, J.	Waterloo	23 000	Einstein's equations and the evolution of cosmological models.
GR-C	Wesson, P.S.	Waterloo	12 000	Tests of particles and fields using spacecraft.
GR-C	Couchman, H.M.P.	Western	35 000	Formation of cosmic structure.
GR-C	Bartel, N.	York	40 000	Galactic and extragalactic compact radio sources.
		Total grants:	589 900	
GR-M	Israel, W.	Alberta	65 000	Strong gravitational fields.
GR-M	Kunzle, H.P.	Alberta	15 000	Solutions of Einstein-Yang-Mills equations.
GR-M	Schleich, K.	UBC	21 000	Topology and dynamics in classical and quantum cosmolgy.
GR-M	Coley, A.A.	Dalhousie	22 000	Exact and qualitative of cosmological models.
GR-M	Tupper, B.O.J.	UNB	5 000	Spacetimes symmetries in general relativity.
GR-M	Lake, K.W.	Queens	18 000	Gravitation, relativistic astrophysics and cosmology.
GR-M	Coleman, R.A.	Regina	8 000	The mathematical and philosophical foundations of the general theory of relativity and other spacetime theories (group).
GR-M	Dyer, C.C.	Toronto	25 000	Applications of general relativity to cosmology.
GR-M	Cooperstock, F.I.	Victoria	10 000	Problems in general relativity and cosmology.
GR-M	McLenaghan, R.G.	Waterloo	20 000	General relativity and differential geometry.
GR-M	Glass, E.N.	Windsor	6 000	General relativity and relativistic astrophysics.
		Total grants:	215 000	
GR-N	Hobill, D.W.	Calgary	33 000	Computational relativity and gravitation.
GR-N	Poisson, E.	Guelph	30 000	Gravitational-wave generation and radiation reaction in compact binary systems.
GR-N	Mann, P.J.	Western	10 000	Numerical models of gravitational collapse.
		Total grants:	73 000	
GR-P	Gegenberg, J.D.	UNB	15 000	Quantum gravity and topological field theory.
GR-P	Widrow, L.M.	Queens	22 000	Dark matter and the large scale structure of the universe.
GR-P	Mann, R.B.	Waterloo	36 000	Exploring gravity's foundations.
		Total grants:	73 000	
GR-Q	Frolov, V.	Alberta	60 000	Quantum gravity and black hole physics.
GR-Q	Page, D.N.	Alberta	55 000	Quantum gravity, black holes, and cosmology.
GR-Q	Unruh, W.G.	UBC	80 000	Quantum mechanics and gravity.
		Total grants:	195 000	

Table 37: (GSC-17 by field, continued)

AP-G	Gregory, P.C.	UBC	15 000	Cosmic jets and bayesian inference in astrophysics.
AP-G	Menon, T.K.	UBC	5 000	Cosmological evolution of radio sources.
AP-G	Hardy, E.J.	Laval	30 000	Internal structure and evolution of galaxies and of the galactic neighbourhood.
AP-G	Joncas, G.	Laval	27 000	Etude cinematique et dynamique de complexes gazeux galactiques.
AP-G	Roy, J.R.	Laval	35 000	Evolution des galaxies riches en gaz.
AP-G	Carigran, C.	Montréal	25 000	Distribution de masse dans les galaxies spirales et naines.
AP-G	Demers, S.	Montréal	25 000	Nearby dwarf galaxies.
AP-G	Hanes, D.A.	Queens	20 000	Extragalactic globular cluster systems; the cosmic scale distance.
AP-G	Irwin, J.A.	Queens	23 000	Winds, jets, bubbles and fountains - a study of gas flows within and around galaxies.
AP-G	West, M.J.	Saint Mary's	20 000	The formation of cD galaxies.
AP-G	Lilly, S.J.	Toronto	55 000	Galaxies at high redshifts.
AP-G	Martin, P.G.	Toronto	50 000	Inquires into the galactic ecosystem.
AP-G	Dawson, P.C.	Trent	14 000	Galactic structure and stellar populations.
AP-G	Harris, G.L.H	Waterloo	12 000	Extragalactic globular cluster systems and galaxy halos.
AP-G	De Roberts, M.M.	York	30 000	Investigations of activity in galactic nuclei.
AP-G	McCall, M.L.	York	30 000	The chemistry of galaxies.
		Total grants:	416 000	
AP-S	Nelson, L.A.	Bishops	17 500	Theoretical investigations of very low-mass stars and binaries containing compact objects.
AP-S	Matthews, J.M.	UBC	25 000	Pulsating stars as diagnostic tools in astrophysics.
AP-S	Richer, H.B.	UBC	47 000	Star and cluster formation in the early universe.
AP-S	Kwok, S.	Calgary	50 000	Effects of mass loss on the late stages of stellar evolution.
AP-S	Milone, E.F.	Calgary	21 000	Variable stars as tracers of stellar evolution.
AP-S	Venkatesan, D.	Calgary	10 000	Space physics and astronomy.
AP-S	Pineault, S.	Laval	12 000	Supernova remnants and stellar winds in the interstellar medium, and compact objects.
AP-S	Harris, W.E.	McMaster	50 000	Old stellar systems in galaxies.
AP-S	Pudritz, R.E	McMaster	45 000	Formation of stars and globular cluster systems.
AP-S	Welch, D.L.	McMaster	35 000	Effects of metallicity on cepheid variable properties.
AP-S	Forbes, D.W.	Memorial	6 000	Star formation and evolution in young clusters and OB associations.
AP-S	Bastien, P.	Montréal	30 000	Etudes theoriques et observationnelles de la formation des etoiles.
AP-S	Fontaine, G.	Montréal	105 000	Etudes des proprietes physiques des etoiles naines blanches (group).
AP-S	Michaud, G.J.	Montréal	60 000	Abondance des elements et hydrodynamique stellaire.
AP-S	Wesemael, F.	Montréal	group	Propriete atmospheriques des etoiles naines blanches et sous-naines.
AP-S	Hughes, V.A.	Queens	10 000	Star formation and the interstellar medium.
AP-S	Bergbusch, P.A.	Regina	6 000	Luminosity and temperature functions for old stellar systems.
AP-S	Guenther, D.B.	Saint Mary's	15 000	Seismology of the sun and stars as a test of stellar structure and evolution.
AP-S	Mitchell, G.F.	Saint Mary's	47 000	Molecular clouds and star formation.

Table 37: (GSC-17 by field, continued)

AP-S	Turner, D.G.	Saint Mary's	18 000	Open clusters and cepheid variables.
AP-S	Bolton, C.T.	Toronto	28 000	Fundamental properties and atmospheres of OB stars.
AP-S	Clement, C.M.	Toronto	9 000	Study of variable stars in globular clusters.
AP-S	Clement, M.J.Y.	Toronto	5 000	Equillibrium and stability of rapidly rotating stars.
AP-S	Fernie, J.D.	Toronto	21 000	Variable star research.
AP-S	Murray, N.W.	Toronto	25 000	Applications of dynamics in the solar system and active galactic nuclei.
AP-S	Percy, J.R.	Toronto	19 000	Studies of variable stars.
AP-S	Hartwick, F.D.A.	Victoria	35 000	Evolution of stars and galaxies.
AP-S	Pritchet, C.J.	Victoria	60 000	Structure and evolution of stellar systems.
AP-S	Vandenburg, D.A.	Victoria	65 000	Absolute/relative ages and mass functions of globular clusters.
AP-S	Duley, W.W.	Waterloo	75 000	Physics and chemistry of interstellar matter.
AP-S	Fich, M.	Waterloo	14 000	Star formation and the interstellar medium.
AP-S	Gray, D.F.	Western	65 000	Dynamics of stellar atmospheres.
AP-S	Landstreet, J.D.	Western	55 000	Magnetic fields/chemical abundances/velocity fields in main sequence A/B stars.
AP-S	Marlborough, J.M.	Western	27 000	Kinematical and dynamical structure of the circumstellar matter around hot stars.
AP-S	Mitalas, R.	Western	5 000	Stellar structure and evolution.
AP-S	Innanen, K.A.	York	30 000	Studies in galactic, stellar and planetary dynamics.
AP-S	Kingsburgh, R.L.	York	18 000	Study of abundances in stellar populations as a function of metallicity.
AP-S	Rucinski, S.M.	York	28 000	Formation and evolution of contact binary stars.
		Total grants:	1 193 500	
AP-T	Leahy, D.A.	Calgary	25 000	High energy phenomena in astrophysics.
AP-T	Sutherland, P.G.	McMaster	25 000	Theoretical astrophysics: supernovae and smoothed particle hydrodynamics.
AP-T	Summers, D.	Memorial	30 000	Studies in theoretical space physics.
AP-T	Clarke, D.A.	Saint Mary's	21 000	Numerical simulations of astrophysical gas dynamics.
		Total grants:	101 000	
AT-E	Cogger, L.L.	Calgary	53 000	Investigation of the Earth's aurora by means of UV imagers on orbiting satellites.
AT-E	Knudsen, D.	Calgary	23 000	Auroral particle acceleration at subkilometer scales.
AT-E	Murphree, J.S.	Calgary	60 000	Usage of auroral images for magnetospheric study.
AT-E	Yau, A.	Calgary	25 000	Polar ionospheric energization and transport.
AT-E	Davis, G.R.	Sask.	30 000	Infrared spectroscopy of terrestrial and planetary atmospheres.
AT-E	Koehler, J.A.R.	Sask.	75 000	Coherent vhf cw doppler radar - polarimeter studies of radar aurora and foward scatter (group).
AT-E	Koustov, A.	Sask.	18 000	Multi-instrumental studies of the high-latitude ionospheric and magnetospheric processes.
AT-E	Llewelyn, E.J.	Sask.	50 000	Aeronomy of the terrestrial atmosphere.

Table 37: (GSC-17 by field, continued)

AT-E	Manson, A.H.	Sask.	95 000	Dynamics of the middle atmosphere (60-110km) based on Saskatoon MF radars and collaborations with regional, glogal and satellite systems/networks.
AT-E	McEwen, D.J.	Sask.	30 000	Auroral processes.
AT-E	Oznovich, I.	Sask.	15 000	Airglow studies of the arctic upper mesosphere and lower thermosphere.
AT-E	Steele, D.P.	Sask.	10 000	Polar diffuse aurora and its magnetospheric implications.
AT-E	Lowe, R.P.	Western	15 000	Optical characterization of middle atmosphere gravity waves.
AT-E	MacDougall, J.W.	Western	10 000	Ionospheric studies using radars.
AT-E	Sica, R.J.	Western	35 000	High temporal-spatial resolution measurements of atmospheric coupling.
AT-E	St. Maurice, J.P.	Western	50 000	Small scale processes in auroral physics.
AT-E	Gault, W.A.	York	10 000	Optical measurements of upper atmosphere winds at Resolute Bay, NWT.
AT-E	McConnell, J.C.	York	35 000	Chemistry and dynamical interaction in planetary atmospheres.
AT-E	McDade, I.C.	York	18 000	Airglow mechanisms and atmospheric composition studies.
AT-E	Nicholls, R.W.	York	15 000	Space spectrscopy: maps, hires, photodissociation.
AT-E	Shepard, G.G.	York	65 000	Global dynamics of the mesosphere and thermosphere.
		Total grants:	737 000	
AT-T	Rankin, R.	Alberta	20 000	Nonlinear magnetohydrodynamic processes in auroral structures.
AT-T	Rostoker, G.	Alberta	80 000	The physics of the solar-terrestrial interaction.
AT-T	Samson, J.C.	Alberta	50 000	Magnetohydrodynamic waves and substorms.
AT-T	Hearn, D.J.	Calgary	12 000	The relation between the auroral distribution and magnetospheric processes.
AT-T	Hamza, A.M.	UNB	20 000	Plasma turbulence in auroral and solar physics.
AT-T	Timothy, J.G.	UNB	35 000	Physics of solar and stellar atmospheres and of solar-terrestrial relationships.
AT-T	Horita, R.E.	Victoria	5 000	Theory of plasma waves and its application in space physics.
AT-T	Hocking, W.K.	Western	45 000	Coupling of wave motions and turbulence in the earth's middle atmosphere.
AT-T	Moorcroft, D.R.	Western	40 000	Studies of ionospheric structure.
AT-T	Laframboise, J.G.	York	33 000	Theory of electrode devices in plasmas, and spacecraft-plasma interactions.
		Total grants:	340 000	
OB-E	Hube, D.P.	Alberta	9 000	Observational studies of binary and variable stars, and of supernova remnants.
OB-E	Landbecker, T.L.	Alberta	18 000	Radio astronomy instrumentation and interstellar medium research.
OB-E	Routledge,D.	Alberta	10 000	Instrumentation for radio astronomy, and interstellar medium research.
OB-E	Vaneldik, J.F.	Alberta	18 000	Radio astronomy receiving systems supernova renmants.
OB-E	Gulliver, A.F.	Brandon	9 000	High dispersion spectroscopy of early-type stars.

Table 37: (GSC-17 by field, continued)

OB-E	Rice, J.B.	Brandon	15 000	Doppler imaging of the surfaces of active stars.
OB-E	Fahlman, G.G.	UBC	47 000	Photometric and spectroscopic studies of stars and stellar systems.
OB-E	Hickson, P.	UBC	40 000	Cosmology with large liquid mirror telescopes.
OB-E	Underhill, A.B.	UBC	14 000	Spectra of o and wolf-rayet stars.
OB-E	Walker, G.A.H.	UBC	60 000	Stellar astronomy.
OB-E	Clark, T.A.	Calgary	6 000	Infrared and submillimeter spectroscopic studies of the solar photosphere and chromosphere.
OB-E	Taylor, A.R.	Calgary	50 000	Radio astrophysics of stars and related galactic phenomena.
OB-E	Borra, E.F.	Laval	40 000	Liquid mirror telescopes.
OB-E	Naylor, D.A.	Lethbridge	33 000	Far IR spectroscopy of the atmospheres of giant planets.
OB-E	Moffat, A.F.J.	Montréal	55 000	Objects of high luminosity and structure of the galaxy.
OB-E	Nadeau, D.	Montréal	24 000	Astronomie infrarouge des regions de formation d'etoiles et des galaxies.
OB-E	Racine, R.	Montréal	46 000	Amas globularies et halos galactiques/imagerie haute resolution.
OB-E	Garrison, R.F.	Toronto	26 000	Classification of stellar spectra.
OB-E	Kronberg, P.P.	Toronto	70 000	Observation-based studies of galaxies, quasars, cosmic magnetic fields, and the starburst phenomenon.
OB-E	Lester, J.B.	Toronto	20 000	Quantitative spectroscopic studies of the atmosphere of luminous cool stars.
OB-E	Mochnacki, S.W.	Toronto	9 000	Mapping the photoshperes of close binary stars.
OB-E	Seaquist, E.R.	Toronto	75 000	Radio studies of circumstellar envelopes and extragalactic star formation.
OB-E	Yee, H.K.C.	Toronto	50 000	The CNOC redshift surveys: the universe at intermediate redshift.
OB-E	Gower, A.C.	Victoria	11 000	Radio studies of quasars, radiogalaxies and galactic systems.
OB-E	Richardson, E.H.	Victoria	7 000	Optical designs of telescopes and spectrographs for earth and space.
OB-E	Scarfe, C.D.	Victoria	6 000	Studies of binary and multiple stars, and of open cluster evolution in the near infrared.
OB-E	Wehlau, A.F.	Western	6 000	Studies of pulsating variable stars.
OB-E	Caldwell, J.J	York	30 000	Planetary studies with Hubble Space Telescope and with ground-based telescopes.
		Total grants:	804 000	
PS-E	Hawkes, R.L.	Mount Allison	8 000	Structure of cometary, asteroidal, and hyperbolic meteoroids.
PS-E	Jones, J.	Western	18 000	Meteor studies.
PS-E	Stooke, P.J.	Western	5 000	Geological mapping of planetary surfaces.
		Total grants:	31 000	

E The Questionnaire

The following pages give the questionnaire and covering letter mailed out to all grantees supported by GSC's 17, 19 and 29, as well as all members of CAP and all Heads of Physics Departments. The same questionnaire was also used for GSC-28, augmented by a few supplementary questions concerning specific issues relating to condensed matter physics. For the GSC's 17 and 29 covered by this report, 69 responses were received. These were distributed as follows:

- GSC-29: 52 out of a total population of 141, or 37%,
- GSC-17: 15 out of a total population of 152, or 10%. Of these, five were from members of the general relativity community.
- Other: 2 from individuals not supported by NSERC.

The low response rate from members of GSC-17 presumably reflects their closer affiliation with CASCA (Canadian Astronomical Society) than with CAP.

July 22, 1996.

Dear Colleague:

We need your help. As you know, most of the Physics allocations from NSERC suffered in the 1994 grant re-allocation exercise, and the next round is scheduled for 1998. Based on a detailed proposal by CAP, NSERC has provided funds for a thorough independent review of physics research in Canada. The reports resulting from this review will provide input to the preparation of the various GSC submissions to the 1998 NSERC Re-allocation Committee. Each GSC has the right to prepare its own submission. It goes without saying that it is very important to prepare the best possible submissions.

The Main Committee charged with the task of undertaking a review of physics research in Canada has been divided into the following subcommittees:

1. Condensed Matter
2. General/Atmospheric/Space Physics and General Relativity
3. Subatomic Physics
4. Highly Qualified Personnel/Economic Aspects

This letter and questionnaire is addressed to researchers in the area of General/Atmospheric/Space Physics and General Relativity. The membership and chairs of each subcommittee are listed at the end of the questionnaire. Note that this division into subcommittees is only for purposes of undertaking a survey of physics as broadly defined, and it does not imply a similar grouping for purposes of preparing final submissions to the NSERC Re-allocation Committee. The intent is for each GSC to prepare its own final submission, using the results of this survey as input.

Please give some time and thought to the enclosed questionnaire. Your answers will form an important part of the review process, and all members of the research community are expected to reply. Although many of the questions are directed to NSERC grant holders, responses from other faculty, postdoctoral fellows and research associates are also encouraged. The questionnaire is divided into the following sections:

I. Personal Statistical Information
II. Personal Research Contributions
III Canadian Strengths and Weaknesses in Physics Research
IV. Selectivity and the Use of Available Funding
V. Vision for the Future
VI. Physics Students and Graduates
VII. Other Comments and Recommendations

Please answer all of Sections I and II, fill out the table on physics graduates in Section VI, and complete those parts of the rest as applicable for which you have comments to make. Use additional sheets of paper if there is not sufficient space on the form. Alternatively, replies can be entered directly into the LaTeX file for the questionnaire. It can be obtained by downloading it by anonymous ftp from cepheid.physics.utoronto.ca (see pub/physics), or http://cepheid.physics.utoronto.ca/Review.

INITIAL REPLIES ARE REQUESTED BY AUGUST 16, 1996. Current grant holders who do not reply by then will be contacted by a member of the Review Committee. For this reason, and for purposes of obtaining follow-up information, respondents are asked to identify themselves. However, replies will be held in confidence, and only reported in a way that does not reveal the identities of individuals to NSERC or others. Respondents who do not wish to have their name on the form may leave this part blank, and supply the requested contact information on a separate sheet of paper.

While NSERC is providing valuable logistical and financial assistance in conducting the review, it does not wish to influence the outcome, nor does it necessarily endorse it. The recipients of this mailing have been identified by NSERC, and the names of individuals on the mailing list have not been disclosed to the members of the subcommittee. Thus, you can choose whether or not to participate in this review. Similarly, while CAP was directly involved in setting up the process and selecting the Canadian subcommittee members, it has no control of the process beyond that stage. Direct CAP participation will be limited to a subcommittee collecting data on the training of highly qualified personnel, chaired by Bev Robertson, the current President of CAP. Thus CAP also does not necessarily endorse the outcome of the research review process.

Finally, if you are not already a member of the Canadian Association of Physicists (CAP), then **please join** (phone 613-562-5614, fax 613-562-5615). It is becoming increasingly clear that research in physics, and in science generally, will only thrive in the present climate if we have strong and united representation at the political level. Paul Vincett, past president of CAP, has done a phenomenal job over the past year in lobbying the federal government on crucial funding issues, such as adequate funding to NSERC and the growing crisis in infrastructure support, but we need your backing as a member of CAP to strengthen these efforts.

Replies should be sent to the appropriate committee chair, as listed at the end of the questionnaire. Many thanks for your co-operation.

Yours sincerely,

Gordon W. F. Drake,
Chair, General/Atmospheric/SpacePhysics
and General Relativity Committee.

SURVEY OF PHYSICS AND SPACE SCIENCE RESEARCH IN CANADA

Name	Position
Address	Telephone
	Fax
	e-mail

I. PERSONAL STATISTICAL INFORMATION

1. Please identify yourself as one of the following:

   ☐ NSERC funded faculty ☐ non-NSERC funded faculty ☐ RA ☐ PDF
   ☐ other ______________________

2. Please identify below ONE of the three major areas which best encompasses your research, together with as many subtopics within that group as are applicable.

☐ CONDENSED MATTER PHYSICS

- ☐ materials science
- ☐ surface science
- ☐ biophysics
- ☐ soft materials
- ☐ pattern formation
- ☐ magnetic properties
- ☐ electronic properties
- ☐ phase transitions
- ☐ semiconductors
- ☐ photonic materials
- ☐ neutron scattering
- ☐ x-ray and synchrotron
- ☐ materials growth
- ☐ materials modification
- ☐ materials characterization
- ☐ computational materials science
- ☐ superconductivity (normal)
- ☐ superconductivity (high T_c)
- ☐ mesoscopic properties
- ☐ highly correlated electron systems
- ☐ other ______________________

☐ GENERAL/ATMOSPHERIC/SPACE PHYSICS AND GENERAL RELATIVITY

- ☐ spectroscopy, atomic and molecular
- ☐ collisions, atomic and molecular
- ☐ other atomic & molecular properties
- ☐ optical physics
- ☐ laser physics
- ☐ plasma physics
- ☐ controlled fusion
- ☐ surface interactions
- ☐ photonics
- ☐ materials science
- ☐ atmospheric physics
- ☐ space science
- ☐ astrophysics
- ☐ general relativity
- ☐ fundamental physics and QED
- ☐ subatomic physics
- ☐ other ______________________

☐ SUBATOMIC PHYSICS

3. Is your research primarily experimental or theoretical?

   □ experimental   □ theoretical

4. What is the current size of your NSERC research grant? $__________ /annum.

5. If you receive other forms of NSERC support (excluding equipment grants), please complete the following:

   (a) Type of grant ____
   (b) Project title ____
   (c) Principal investigator ____
   (d) Number of participants _____
   (e) Annual budget $__________

6. Please list any other sources of research funding and the amounts.

   Canadian:

   source ____ $__________ /annum

   source ____ $__________ /annum

   Foreign:

   source ____ $__________ /annum

   source ____ $__________ /annum

7. Please provide information on the following statistical indicators of impact.

   (a) Number of refereed journal publications:

       Total _____   Last five years _____

   (b) Total number of citations for your top five papers for each of the last five years:

       1995 _____   1994 _____   1993 _____   1992 _____   1991 _____

       (note that the Citations Index is by first author only).

   (c) Number of invited conference papers in the last five years:
       i. Canadian conference _____
       ii. International conference _____
   (d) Number of review articles in the last five years _____
   (e) Honours and awards:

(f) Other forms of recognition:

II. PERSONAL RESEARCH CONTRIBUTIONS

1. Briefly describe your research in nontechnical terms.

2. What opportunities do you see for the future development of your research?

3. Why are these developments important to the advancement of the field?

4. Describe the impact that your work has had on, for example, (a) your particular field of specialization, (b) physics in general, (c) science in general, and/or (d) technological applications.

5. Describe the anticipated impact that proposed future work could have on, for example, (a) your particular field of specialization, (b) physics in general, (c) science in general, and/or (d) technological applications.

6. Describe the impact that you foresee for your subfield on the development of physics in general and/or technological applications.

7. Are you involved in collaborative projects? ☐ YES ☐ NO

   If you answered YES, please answer the following questions:

   (a) Describe the nature of university-based collaborations, including those with other disciplines.

   (b) Describe the nature of collaborations with industry etc.

   (c) Describe the nature of other collaborations (e.g. with NRC)

8. What additional initiatives and progress could you make if your NSERC operating grant were doubled? Include examples of opportunities lost due to underfunding.

9. What would be the adverse effects if your NSERC operating grant were halved? Consider here questions of urgency and priorities.

10. What is the role and importance of university infrastructure (e.g. machine shops, technical support) to your research?

11. Do large central facilities such as synchrotrons play an important role in your research? If so, please outline

    (a) the facilities used

    (b) problems or difficulties

    (c) desirable improvements or enhancements

12. Could your research benefit from large scale computing facilities? If so, please outline.

13. Are there other areas of research that you draw upon in your work? If so, please describe.

III. CANADIAN STRENGTHS AND WEAKNESSES IN PHYSICS RESEARCH

1. What do you believe are the current areas of strength in Canada for physics research, rated on an international scale? Please elaborate.

2. What do you believe are the current areas of weakness in Canada for physics research, rated on an international scale? Please elaborate.

3. Weaknesses might include important new or emerging areas. Should these be strengthened? If so, at the expense of what?

4. In view of the above, should there be particular areas of focus for Canada in the future, and if so, which?

5. What steps should be taken by NSERC or the research community to ensure that a defined area of focus does not unduly diminish research diversity and risk-taking?

6. Describe any anecdotal “success stories” you might know involving industrial or interdisciplinary applications of Canadian physics in either your own area of research, or in other areas.

IV. SELECTIVITY AND THE USE OF AVAILABLE FUNDING

In order to accomplish best the objectives for physics research in Canada within the available funding, the Grant Selection Committees (GSCs) must decide how selective to be in awarding grants. Should the most productive researchers be supported at an internationally competitive level? If so, at whose expense? Are there other special concerns to be taken into account?

1. With these considerations in mind, do you think that the Physics GSC’s should be
   - ☐ more selective
   - ☐ about the same
   - ☐ less selective
   - ☐ other, see rationale below

   Outline the rationale for your recommendation.

2. Are there special considerations that should be taken into account regarding
   (a) regional and geographical distribution?

   (b) support of researchers in smaller universities?

   (c) risk-taking and diversity of research?

3. Do you believe in the concept of a minimum useful grant, and if so what level(s) would be appropriate?

4. Do you believe that there should be some maximum level(s) for the funding of an individual in the research grants program, and if so what should it(they) be?

5. Do you have any comments on the present situation regarding startup grants for new researchers? If you propose increased funding, where should it come from?

6. Do you have any comments on the NSERC equipment and major equipment funding programs?

7. Given the growing emphasis on research partnerships, particularly with industry, should those in less industrially developed parts of Canada be helped in their participation? If so, can you suggest mechanisms?

8. What strategies should NSERC adopt regarding:

   (a) risk-taking (i.e. the support of speculative proposals with with limited chances of success, but large potential pay-offs)

   (b) encouragement of spin-off activities and ventures

   (c) better communication of research results to other disciplines and to the public

(d) greater participation of physicists in interdisciplinary research

9. How can the impact of Canadian physics research on other disciplines be enhanced?

10. Could the overall health of Canadian physics (or a particular subdiscipline) be enhanced by a major collaborative effort across physics boundaries and/or across other disciplines? If so, please elaborate.

V. VISION FOR THE FUTURE

The areas of research covered by the various Physics GSC's are diverse. Nevertheless, one of the strengths of physics lies in its search for the principles underlying diverse phenomena, and the unification of understanding. Physicists have a long history of recognizing the importance of new phenomena and developing new applications. Within this context, please consider the following questions:

1. What exciting themes do you see emerging (or already exist) in your own area of research, and its relationship to others?

2. What themes should be encouraged in the broader context of physics research in Canada? Are there particular areas of research that should be emphasized?

3. Do you see opportunities for new or continuing interdisciplinary research?

4. What should be the attitude of our community to the role of applied research?

VI. PHYSICS STUDENTS AND GRADUATES

1. How many students have graduated from your research group in the last five years?

   M.Sc. number _____ Ph.D. number _____

2. How many of these are currently employed as physicists, or in closely related disciplines?

   M.Sc. number in Canada _____ Ph.D. number in Canada _____

   M.Sc. number elsewhere _____ Ph.D. number elsewhere _____

3. Can you cite examples of graduate students carrying technological skills or innovations from their research into industry?

4. How might technological transfer by students from universities to industry be improved?

5. Do you feel that student training and/or employment prospects can be enhanced by direct contact with industrial research or collaboration with industry? Has this played any part in your research program?

6. Does physics research play a role in your undergraduate program (e.g. honours thesis projects), or do you hire undergraduate students as research assistants? If so, please elaborate.

7. Do you think that your involvement in research makes your teaching

   □ much better □ better □ the same □ worse □ much worse.

8. What do you perceive are the unique benefits that a student should obtain from a physics education (especially undergraduate)?

9. Please fill in the following table with the names of your M.Sc. or Ph.D. students who have graduated over the past six years (July 1990 to July 1996), and also postdoctoral fellows (PDF) or research associates (RA) who left your group during this period. Include their current occupation, or indicate their position if currently a PDF, RA, or technician (T).

Name	Position or Degree	Year	Current Occupation or Position	Employer/Location

VII. OTHER COMMENTS OR RECOMMENDATIONS

Depending on the major area of research selected in Question I.2, please return to one of:

CONDENSED MATTER PHYSICS	Prof. Michael Thewalt Department of Physics Simon Fraser University Burnaby, BC V5A 1S6	e-mail: Fax: Tel:	Thewalt@sfu.ca (604) 291-3592 (604) 291-3384
GENERAL/ATMOS./ SPACE PHYSICS AND GENERAL RELATIVITY	Prof. Gordon Drake Department of Physics University of Windsor Windsor, ON N9B 3P4	e-mail: Fax: Tel:	A36@server.uwindsor.ca (519) 973- 7075 (519) 253-4232 Ext. 2656.
SUBATOMIC PHYSICS	Prof. Pekka K. Sinervo Department of Physics University of Toronto Toronto, ON M5S 1A7	e-mail: Fax: Tel:	pekka@physics.utoronto.ca (416) 978-8221 (416) 978-5270

Main Committee

Bill Halperin (Northwestern Univ.) Chair Halperin@casbah.acns.nwu.edu.

Condensed Matter

Mike Thewalt (SFU)	Chair	Thewalt@sfu.ca
John Berlinsky (McMaster)	High T_c superconductors, theoretical aspects of electronic states/magnetism	Berlinsk@mcmail.CIS .mcmaster.ca
Martin Grant (McGill)	Soft condensed matter, statistical mechanics, polymers	Grant@physics.mcgill.ca
Thom Mason (U. of Toronto)	Neutron/synchrotron scattering, experimental aspects of magnetism, heavy fermion systems	Mason@physics.utoronto.ca
Sjoerd Roorda (U. Montréal)	Surface and applied physics, ions beams for CM research	Roorda@LPS.umontreal.ca
Jeff Young (UBC)	Semiconductors, heterostructures, nanostructures, mesoscopic systems	Young@physics.ubc.ca

General/Space/Atmospheric Physics/General Relativity

Gordon Drake (Windsor)	Chair	A36@server.uwindsor.ca
Paul Corkum (NRC)	Laser physics/spectroscopy/optics	Paul.Corkum@nrc.ca
Bill McConkey (Windsor)	Atomic and molecular scattering	Mcconk@server.uwindsor.ca
Tudor Johnston (INRS)	Plasma physics	johnston@inrs- ener.uquebec.ca
Bill Unruh (UBC)	General Relativity	Unruh@physics.ubc.ca
Henry van Driel (U Toronto)	General physics applications	Vandriel@physics.utoronto.ca
Ted Llewellyn (U. Sask)	Atmospheric and Space	Llewellyn@skisas.usask.ca

SubAtomic Physics

Faqir Khanna (Alberta)	Chair	Khanna@phys.ualberta.ca
Pekka Sinervo (Toronto)	Particle physics, and co-chair	Pekka@physics.utoronto.ca
Jean-Michel Poutissou (TRIUMF)	Medium/high energy physics	JMP@triumf.ca
Richard Keeler (Victoria)	Particle physics	RKeeler@uvic.ca
Jean Barrette (McGill)	Heavy Ions	Barrette@physics.mcgill.ca
Aksel Hallin (Queens)	SNO	Hallin@mips2.phy.queensu.ca

HQP / Economic Aspects (CAP Committee)

Bev Robertson (Regina), Chair	Robertsb@leroy.cc.uregina.ca
Paul Vincett (FairCopy)	Paul_Vincett@torho.xc.xerox.ca
Ted Dixon (U Waterloo, and Waterloo Scientific)	AEDixon@uwaterloo.ca
Gordon Rostoker (Alberta)	Rostoker@space.ualberta.ca
John de la Mothe (U. Ottawa)	
George Beer (U. Victoria)	Beer@uvphs.uvic.ca

F Glossary of Technical Terms

Attosecond (as): A time interval of 10^{-18} second.

Autodetaching state: a doubly excited electronic state of a negative ion that decays primarily by the emission of an electron to form a neutral atom.

Autoionizing state: a doubly excited electronic state of an atom or positive ion that decays primarily by the emission of an electron to form a more highly charged ion and a free electron.

Betatron: a device for accelerating charged particles, especially electrons (and hence the name), by continuously increasing the magnetic field within the particle's orbit. The time-varying magnetic flux produces an accelerating potential.

Biophotonics: the study of the interaction of photons, and especially laser light, with biological materials as a method to study their properties, treat diseases etc.

Black hole: the region of space surrounding a collapsed massive object such as a star where the force of gravity is so strong that the escape velocity exceeds the velocity of light.

Brillouin scattering: the scattering of light by transitory and localized thermally driven fluctuations or waves (acoustic waves) in the density of a fluid.

Circular dichroism: the preferential absorption of either right handed or left handed circularly polarized light as it passes through an optically active medium. As a consequence, linearly polarized light becomes elliptically polarized.

Chaos: the property of a physical system to show great sensitivity in its time evolution to its initial conditions (e.g. the rolling of a die). Even though the time evolution may be in principle deterministic, the final state of the system becomes unpredictable for all practical purposes. Nevertheless, such systems show suprising regularities and universal properties.

Chirped pulse amplification (CPA): a technique for obtaining very high peak laser powers in which a laser pulse is first chirped (i.e. spread out across a broader range of frequencies) by passing it through a nonlinear optical medium such as a glass fibre. The chirped pulse is then amplified, and finally compressed in time by means of a pair of diffraction gratings.

Coherent process: a process involving two or more electromagnetic or matter waves in which there is a definite phase relationship among the various wave components; i.e. the waves move "in step", and can thus interfere with one another.

Dissociation limit: the limit approached by the vibrationally excited states of a molecule where the energy of vibration becomes so great that the molecule separates into independent fragments.

Doppler broadening: a broadening of spectral lines emitted by atoms due to their random thermal motion.

Doppler-free spectroscopy: a technique to eliminate the Doppler broadening of spectral lines by, for example, the use of counter-propagating laser beams to select a subsample of atoms all moving with the same velocity.

Opto-electronics: techniques for the use of light to control electrical currents, usually in semiconductors.

Equation of state (EOS): a functional relation among the directly observable properties of a system. For a fluid or plasma, these are the temperature, pressure and volume, together with other pairs of quantities such as magnetic field and magnetization, and/or electric field and polarization.

Faraday effect: a rotation of the plane of polarization of polarized light as it passes through a magnetically active medium.

Femtosecond (fs): a time interval of 10^{-15} second.

Fourier transform spectroscopy: a technique in which the spectrum of a beam of incident infrared radiation is obtained by first generating and recording an interferogram with a scanning Michelson interferometer. Subsequently the interferogram is inverted by means of a Fourier transform into the frequency spectrum. The technique can automatically distinguish between the absorption and emission spectrum of the sample.

General relativity: the generalization of Einstein's theory of relativity to include the effects of gravity and accelerating frames of reference, thereby replacing Newton's theory of gravity by a more comprehensive theory in which gravity becomes a geometrical property of space-time.

Gravity wave: in general relativity, the gravitational analogue of an electromagnetic wave propagating through space with the velocity of light.

Inertial confinement fusion (ICF): a process designed to induce thermonuclear fusion in which heating and compression are achieved by the impact of high-power lasers on a small fuel pellet. An outer shell of material is ablated outward while the remainder of the material recoils inward in a laser-indused implosion.

Infrared: the region of the electromegnetic spectrum with wavelengths longer than the visible range of 400 to 700 nm.

Interference: in optics or quantum mechanics, the propensity of coherent waves from different sources to reinforce each other (constructive interference) or cancel each other (destructive interference), depending on their relative phase at each point in space.

Line shape: the intensity profile of a spectroscopic line as a function of wavelength or frequency. See also *Linewidth*.

Linewidth: the frequency interval over which a nominally sharp spectroscopic "line" is spread. The term "line" arises historically from the line-like trace on a photographic plate produced by light of a single pure frequency after passing through a spectrograph.

Magnetic confinement fusion (MCF): a process in which thermonuclear fusion is made to occur between light atomic nuclei of atoms heated to a high temperature and confined in a magnetic "bottle".

Magnetic rotation spectroscopy: a technique that uses the magnetic properties of a sample in effect to rotate the plane of polarization of laser radiation (by use of the Faraday effect and/or magnetic circular dichroism) and thereby probe the energy levels of the system being examined.

Monte Carlo method: a computational method in which the answer to a complex problem is gradually built up by the use of random sampling techniques (and hence the name).

Opto-electronics: the use of light to control electrical signals, or vice versa, often through the use of optically active surface coatings.

Oscillator strength: a measure of the relative strength (brightness) of various atomic and molecular transitions accompanying the emission or absorption of light.

Particle physics: the study of the elementary particles of nature and their interactions, especially through the use of high-energy particle accelerators.

Photoionization: the ejection of an electron from an atom or ion (ionization) by the absorption of a sufficiently energetic photon.

Photonics: a broad term referring to the design and construction of devices for the control and manipulation of photons, especially lasers and their interaction with matter. In this sense, the term is analogous to *electronics*, meaning devices for the control and manipulation of electrons or electrical currents.

Picosecond (ps): a time interval of 10^{-12} second.

Plasma: a state of matter in which a substantial fraction of the atoms or molecules are ionized to form free ions and electrons.

Quantum electrodynamics: a unified quantum theory providing a precise description of electrons (or other charged particles such as muons), photons, and their interactions.

Raman scattering: a nonlinear two-photon optical process in which an atom or molecule converts an incident photon of frequency ν_1 into a scattered photon of frequency ν_2 with the energy difference $h(\nu_1 - \nu_2)$ being taken up by a transition in the scattering atom or molecule. The process of stimulated Raman scattering (SRS) (analogous to stimulated emission) is useful in converting laser frequencies or amplifying pulses.

Rydberg state: one of a sequence of electronically excited states of an atom, ion, or molecule.

Soliton: a wave-like disturbance in a medium that can propagate indefinitely without change in shape due to the nonlinear properties of the medium.

Spectral line shape: See *Line shape.*

String theory: a class of theories based on a unified description of all elementary particles and the forces that act among them in terms of one-dimensional curves called "strings", rather than point-like particles. The characteristic length scale for the strings is the Planck length $L_{\mathrm{Pl}} \sim 1.6 \times 10^{-33}$ cm.

Synchrotron radiation: light (expecially ultraviolet and x-ray) produced by electrons as they are accelerated to high velocity in a circular ring device.

Terawatt (TW): a unit of power equal to 10^{12} watts.

Tokamak: a device for magnetic confinement fusion in which a plasma current is induced around the axis of a torroidal vessel by the sudden pulsing of an external magnetic field. The current in the plasma causes a poloidal magnetic field which, together with the externally applied magnetic field, confines the plasma.

Ultraviolet (uv): the region of the electromegnetic spectrum with wavelengths shorter than the visible range of 400 to 700 nm.

Vacuum ultraviolet (vuv): the region of the electromagnetic spectrum with wavelengths shorter than about 200 nm where a vacuum is required for transmission because air strongly absorbs radiation at these wavelengths.

van der Waals molecule: a molecule in which the constituent atoms are loosely held together by weak long-range forces.

G List of Acronyms and Abbreviations

μm	micrometer (10^{-6} meter).
AES	Atmospheric Environment Service.
AMO	Atomic, Molecular, and Optical (Physics).
as	attosecond.
CADI	Canadian advanced Digital Ionosonde.
CANOPUS	Canadian Open Unified Study.
CAP	Canadian Association of Physicists.
CCFM	Centre Canadien pour la Fusion Magntique.
CEDAR	Coupling, Energetics and Dynamics of Atmospheric Regions.
CNSR	Canadian Network for Space Research.
CIAR	Canadian Institute for Advanced Research.
CITA	Canadian Institute of Theoretical Astrophysics.
CLS	Canadian Light Source (synchrotron).
COPL	Centre for Optics, Photonics, and Lasers (Laval).
CPA	Cold Plasma Analyzer (plasma physics).
CRESS	Centre for Research in Experimental Space Science (York).
CRM	Centre de Recherche Mathématique (Montréal).
CSA	Canadian Space Agency.
DARN	Dual Auroral Radar Network.
DREV	Defense Research Establishment at Val Cartier.
EOS	Earth Observing System (Atmospheric Physics).
EOS	Equation of State (Plasma Physics).
FCAR	les Fonds pour la Formation de Chercheurs et l'Aide a la Recherche.
fs	femtosecond.
GCM	Global Circulation Model.
GSC	Grant Selection Committee.
HRDI	High Resolution Doppler Interferometer on the UARS spacecraft.
ICF	Inertial Confinement Fusion.
ISTS	Institute for Space and Terrestrial Science.
ITER	International Thermonuclear Experimental Reactor.
LIF	Laser Induced Fluorescence.
LPI	Laser-Plasma Interactions.
MAM	Middle Atmosphere Model.
MCF	Magnetic Confinement Fusion.
MOPITT	Measurement of Pollution in the Troposphere.
MPBT	MPB Technologies.
NIH	National Institute of Health.
NRC	National Research Council.
NSERC	Natural Sciences and Engineering Research Council.
nm	nanometer (10^{-9} meter).
OLLRC	Ontario Laser and Lightwave Research Centre (Toronto).
OSIRIS	Odin Spectrograph Infrared Imaging System.
PAR	Plasma Applications Research.
PI	Principal Investigator.
PSMOS	Planetary Scale Mesopause Observing System.
ps	picosecond.

SAPPHIRE	Saskatchewan Auroral Polarimetric Phased Ionospheric Radar Experiment.
SBS	Stimulated Brillouin Scattering.
SCOSTEP	Scientific Committee on Solar Terrestrial Physics.
SMS	Suprathermal Mass Spectrometer.
SRS	Stimulated Raman Scattering.
STEP	Solar Terrestrial Energy program.
STRAC	the Solar-Terrestrial Relations Advisory Committee of the CSA.
St. FX	Saint Francis Xavier University.
TPA	Thermal Plasma Analyzer.
TW	Terawatt.
UBC	University of British Columbia.
UTIAS	University of Toronto Institute for Aerospace Studies.
UWO	University of Western Ontario.
uv	Ultraviolet.
VLSI	Very Large Scale Integration.
vuv	Vacuum Ultraviolet.
WINDII	Wind Imaging Interferometer on the UARS spacecraft.

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