Cosmic Microwave Background

Space Science Discipline Working Group

Final Report, March 31, 2009

Chair: Matt Dobbs (McGill)

Report Authors: Dick Bond (CITA), Matt Dobbs (McGill), Mark Halpern (UBC), Gil Holder (McGill), Barth Netterfield (U. Toronto), Dmitri Pogosyan (U. Alberta), Douglas Scott (UBC)

Executive Summary

In this report the Cosmic Microwave Background (CMB) Working Group provides a roadmap and recommendations for the next decade of CMB space astronomy in Canada.

Key Science: *How did the Universe begin?* Inflation is the leading theoretical paradigm for describing the first moments after the Big Bang. The 'smoking gun' prediction of favored inflationary models is the existence of an inflationary gravity wave background that imprints a signature on the CMB as a faint curl-component to the polarization pattern on large angular scales. Its detection would be a direct probe of physics at the very highest energies. The primary objective for the decadal roadmap described in this document is a measurement of the CMB-polarization that will allow for the detection of the inflationary gravity wave signature, or an upper bound on its energy scale. These measurements will additionally provide tests of Einstein's gravity on large scales, information about new particles or forces, and possibly new insight on Dark Energy. They will enable a new window on the Universe, creating new knowledge that will continue Canada's tradition of international excellence in this field.

Canadian Expertise: The CMB community in Canada is characterized by a high level of expertise in the Universities, with a strong commitment to training of graduate students. Canadians have established themselves as world leaders in detector electronics, data analysis and associated software, and the design/integration/operation of stratospheric balloon telescopes. For example, experiments around the world using the current generation of more than a couple hundred bolometric detectors share one thing in common: their readout electronics were provided by members of the Canadian CMB community, and Canadians partner in the scientific return of these projects. Canadian academics have begun industrial partnerships to transfer this technology. Trainees are incorporated into every element of the development and operation of experiments, resulting in broadly trained individuals with unparalleled experience in the development and analysis of scientific instruments.

Decadal Roadmap: This Working Group anticipates that there will be one or two more generations of sub-orbital and custom ground-based experiments leading to a major satellite mission to map the polarization of the CMB over the whole sky with sufficient angular resolution to study the gravitational lensing signal and with sensitivity at least an order of magnitude better than any currently designed experiment. As such, the Canadian CMB community foresees significant involvement with the following missions over the next decade

- Planck Satellite, launching in 2009
- EBEX and SPIDER Balloon-borne polarimeters, with science flights from 2009-2013. We expect at least one additional sub-orbital mission to develop this decade.
- An international partnership for a purpose-built CMB Polarization satellite for launch towards the end of the next decade.

This program must be coupled with a rigorous commitment to technology development and personnel training from both the community and funding agencies. This space roadmap will benefit from the community's extensive involvement with ground-based projects.

Recommendations:

- CSA should continue to fund sub-orbital projects on merit through the Small Missions or similar program. The community and the Agency should anticipate another generation of sub-orbital CMB missions after the currently funded set.
- To fund missions for their full lifetime, including data analysis, as long as they demonstrate through periodic peer review that they are scientifically productive. This is especially important for Planck, but it is important for all CMB missions. An expanded SSEP-style for funding post-doctoral fellows would suffice, providing adequate funding is made available.
- Provide continuity of funding for technology development and training of highly qualified personnel, possibly through a new CREATE-like program. Fund technology development within the SSEP program.
- Fund participation as a full partner in an international effort for a mission which will produce ambitious full sky polarization maps of the CMB. The Working Group will be active in the CASCA Long Range Planning exercise to assure that there is broad community support for this mission.

List of DWG Meetings

The Cosmic Microwave Background (CMB) held two formal meetings over the course of its two year mandate. Meeting reports are provided in the appendix of this document.

The first meeting consisted of a 4 day workshop hosted by McGill University in Montreal March 27-31, 2008. Our goals were three fold: (1) study and understand prospects for future space astronomy measurements of the CMB, (2) contribute to the training of highly qualified personnel by dedicating time and resources to expert lectures covering the science and instruments, (3) provide a forum for interactions and discussions on present technology and data reduction/analysis techniques and new results from experiments with direct Canadian involvement. About 40 people attended (including many international participants, who paid all of their own expenses). In addition to CSA DWG contributions, we were able to attract funding from CIfAR and McGill University for this workshop.

The second meeting was a focused one day discussion with senior members of the DWG attending. It was hosted by the University of Toronto February 4, 2009.

In addition to the meetings organized and hosted in Canada, members of the working group have actively participated in the CMBpol Mission Concept Study (CMBpol 2009), attending meetings, contributing to the final report, and authoring whitepapers (e.g. Dobbs and Lee, 2008; Irwin and Halpern, 2008).

Throughout the course of the 2 year term of the DWG there were numerous discussions and meetings by email, telephone, and in person between sub-sets of the group members.

Key science objectives

The Cosmic Microwave Background (CMB) gives us the opportunity to study the Universe at its earliest times, and learn about fundamental physics at the highest accessible energies. The discovery of the CMB taught us that the Universe in the past was very much hotter and denser (the "Big Bang" model), while the measurement of the temperature anisotropies that started with the COBE satellite (Smoot *et al.*, 1992) began telling us about the nature of the seed perturbations from which all the structure in the Universe grew. From a new set of CMB experiments, in particular the WMAP satellite (Hinshaw *et al.*, 2009), we have now learned the approximate values of the half dozen or so parameters which describe the Universe on the largest scales.

Inflation (Guth 1981, Linde 1982, Albrecht and Steinhardt 1982) is the leading theoretical paradigm for describing the first moments after the Big Bang. It is a period, lasting a tiny fraction of a second, in which the Universe undergoes rapid accelerated expansion. This allows microscopic quantum fluctuations to be stretched to cosmic scales, seeding the formation of the large scale structure we observe in the Universe. Inflation provides simple and elegant explanations for the homogeneity of the CMB on super-horizon scales, its nearly scale invariant, Gaussian spectrum of fluctuations, the lack of magnetic monopoles, and the spatially flat geometry of the Universe—all of which have been observed. The 'smoking gun' prediction of most inflationary models is the existence of an inflationary gravity wave background that imprints a distinct signature on the CMB as a faint curl-component to the polarization pattern on large angular scales. In analogy with electromagnetism this component is usually referred to as the "B-mode" signal. The amplitude of this signature is set by the inflationary energy scale and so, although the signal is typically very weak, its detection would be a direct probe of physics at the very highest energies. The strength of the "B-mode" signal is characterized by the parameter r, called the tensor to scalar ratio. While $\boldsymbol{r}$ is essentially unconstrained from attempts to directly observe of B-mode polarization today, indirect measurements from WMAP combined with Baryon Acoustic Oscillations and Super Nova measurements constrain it to $r<0.22$ (Komatsu 2009).

Many models of inflation are still consistent with this limit and with what we know about the CMB anisotropies. With improved measurements of the slope of the density perturbations power spectrum n and stringent limits on the B-modes we will be able to definitively rule out (or verify!) whole sectors of the model space. Planck, together with small-scale CMB experiments like the Atacama Cosmology Telescope (ACT, Kosowsky *et al.*, 2006) and South Pole Telescope (SPT, Ruhl *et al.*, 2006), should yield exquisite measurements of n, while Planck, EBEX and SPIDER will investigate an optimistic range for the B-mode amplitude. When these results are known the direction of the next step will be much clearer, informing the design of a purpose built CMB polarization satellite.

Precision CMB measurements can also be used to constrain the evolution of the Dark Energy, the mysterious negative pressure component of the Universe's energy budget that has a repulsive effect, driving the Universe to accelerate today. Firstly, the CMB last-scattering surface provides an anchor to pin the physics at redshift z=1100, at an age since the Big Bang of aboutr 380,000 years. Other astrophysical measures can then be compared with this. For example, precise estimates of the brightness of supernovae enable the evolution of the Dark Energy to be measured at around z=1. But the full precision of this approach is only possible when used in combination with CMB measurements. The second way in which the CMB can be used to tackle the Dark Energy problem is to search for distinct correlations between CMB and the structure in galaxy distribution which arise as the Dark Energy is evolving at low redshift. There are effects on the large angular-scale CMB anisotropies, caused by variations in gravitational potential wells as the Dark Energy starts to cause large structures to dissolve. There are also correlations between structure in galaxy surveys and gravitational lensing effects on the CMB sky. Extracting these signals is challenging, but if it can be done as a function of redshift, then we will learn directly about the recent evolution of the Dark Energy component.

The first recommendation of the U.S. inter-agency Task Force on CMB Research (Weiss *et al*. 2006) is "a phased program to measure the large-scale CMB polarization signal expected from inflation." This recommendation—testing theories which seed structure formation—is very well aligned with the overall thrust of the last Canadian Astronomy Long Range Plan, which is titled "The Origins of Structure in the Universe". Additionally, the CMB roadmap discussed in this document contributes to a better understanding of essentially all eleven questions of the Report of the Turner Committee to the National Academy of Science in the United States "Connecting Quarks to the Cosmos" (http://www.nap.edu/books/0309074061/html/). Measurements of CMB polarization it the best means of addressing its question, "How did the Universe begin?".

The primary objective for the decadal roadmap described in this document is a measurement of the CMB-polarization that will allow for the detection of the inflationary gravity wave signature for tensor to scalar ratios down to about $\boldsymbol{r}$<0.01. This will allow us to address some of the most profound "how" and "why" questions which grip modern astrophysicists:

- did the very early Universe undergo an inflationary phase of accelerated expansion? can we use the CMB to probe the nature of physics at energies a trillion times higher than with Earth-based accelerators?
- what is the nature of the Dark Energy which makes the Universe accelerate today? Is it related to inflationary acceleration?
- how does gravity behave on the very largest scales? are there any deviations from Einstein's predictions?

In addition, a concerted attack with increasingly sensitive (and higher angular resolution) CMB experiments, many of which will be ground-based (such as ACT and SPT), allows a suite of other questions to be addressed, including:

- how exactly did the Universe become ionized after the first stars formed?
- how did clusters of galaxies form and evolve?
- what is the mass of the neutrino?
- are there subtle correlations ("non-Gaussian" signatures) imprinted on the CMB by fundamental physics?

The roadmap for the next decade outlined in this document is meant to address these questions head-on, with the Canadian CMB community working together and with international partners to design, build, and deploy experiments purpose-built to answer these questions.

Canadian Expertise

The CMB community in Canada is characterized by a high level of expertise in the Universities, spanning a range of critical areas. The strong commitment to graduate student and postdoctoral training is evident from the membership of this working group (refer to the appendix), which includes several trainees for each senior researcher. It has been the tradition of Canadian researchers in this field to include trainees with every element of the development and operation of experiments, resulting in broadly trained individuals with unparalleled experience in the development and analysis of scientific instruments. We outline Canadian expertise in the field below.

Faculty Research Groups:

Dick Bond (CITA): Dick Bond is one of the world experts in the theory and interpretation of CMB data. His group has played central roles over the last three decades in developing the theories that allowed the CMB to be used to constrain cosmological parameters, in developing data analysis techniques which allowed increasingly large data sets to be efficiently and accurately analyzed, and in the analysis and interpretation of a stream of some of the most important CMB experiments to have operated. He is the PI for the Canadian contribution to Planck HFI.

Matt Dobbs (McGill University): Matt Dobbs is an expert in low noise superconducting circuits and digital electronics, applying this expertise to bolometer detector systems. He has demonstrated expertise in the integration, deployment, and commissioning of forefront CMB experiments. He co-led the development of the APEX-SZ and South Pole Telescope bolometer readout systems, and now leads the development of systems for EBEX and POLARBEAR. His group is active in the analysis of data from these instruments. He is the PI for the Canadian contribution to EBEX.

Mark Halpern (UBC): Mark Halpern is an expert in CMB experiment design and electronics. He has developed electronics for a TES detector readout system which will control the focal planes for SCUBA-II, SPUD, BICEP-II, CLOVER and ACT and Spider. He is additionally an expert in the design and integration of orbital (being a member of the core team that designed and realized the WMAP mission) and sub-orbital experiments, including 1 rocket experiment and 4 balloon borne experiments. He has built a cryogenic spectrometer, bolometers, telescopes and guidance systems for flight instruments and his lab has helped bring rigorous map-making techniques to sub-mm astronomy.

Gil Holder (McGill University): Gil Holder is a theorist with expertise in the simulation of CMB observables and the effect of experiment induced systematics on the interpretation of data. He is a member of the South Pole Telescope collaboration and played a leading role in showing the feasibility of experiments for SZ surveys.

Barth Netterfield (U. Toronto): Barth Netterfield is an expert in CMB telescope design, integration, and operation, and in the analysis of CMB data. He has played leadership roles in the hardware and analysis of the Saskatoon experiment, BOOMERANG, BLAST, and now Spider. An expert in stratospheric balloon borne telescopes, he has participated in 7 flights on three different balloon borne experiments, including leading the overall system integration. Additionally, Netterfield is an expert in instrument control and data display software, and has led the Quick Look Analysis software development for Planck

Dmitri Pogosyan (U. Alberta): Dmitri Pogosyan is an expert in the theory of the CMB and theoretical cosmology in general, including the mechanisms for the generation of density inhomogeneities and gravitational waves in the early Universe that are the focus of the upcoming CMB experiments. He has played an active role in the cosmological interpretation of the BOOMERANG and CBI data and is a member of the Canadian contribution to Planck.

Douglas Scott (UBC): Douglas Scott has worked on theoretical predictions of the CMB since before the first COBE results arrived in 1992. He has written more than 50 research papers on CMB theory and data analysis topics, including heavily cited review articles. He is the PI for the Canadian contribution to Planck LFI.

Areas of Expertise and facilities:

Data analysis: Canada continues to be a world leader in the analysis of CMB data, with Canadian researchers playing key roles in the analysis of many of the most important CMB experiments over the past 20 years, including FIRS, Saskatoon, BAM, BOOMERANG, CBI, ACBAR, WMAP, APEX-SZ, ACT, and SPT. The analysis of these experiments is integral to the training of a stream post-docs and graduate students, many of whom have gone on to faculty jobs around the world, and the ongoing opportunities continue to attract excellent graduate students and post-docs into the programs. As well as the first rate expertise in data analysis, Canadian researchers enjoy access to excellent computing resources, including WestGrid, the CITA clusters, and SciNet—a critical factor in the increasingly complex analysis of next-generation experiments.

Detector Electronics: Around the world, the current generation of bolometric detectors using more than a couple hundred detectors share one thing in common: their readout electronics were provided by members of the Canadian CMB community. This includes detector readout electronics for ACT, BICEP-II, BLAST, CLOVER, EBEX, APEX-SZ, Keck/SPUD, PIPER, SPT, Spider, and SCUBA-II. The continued advancement of these technologies has continued open doors to Canadian researchers into the next generation of experiments. In particular, Canadians have been instrumental in developing multiplexed readout electronics, a key technology for experiments with a thousand or more bolometric detectors (refer to Dobbs and Lee 2008 and Irwin and Halpern 2008 for reviews and see the technology section of this report). The readout electronics and detector characterization program in Canada is supported by dedicated labs at UBC and McGill for readout/detector systems development.

Stratospheric Balloon Telescope Design, Integration and Operation: Canadian researchers have provided design and integration expertise in some of the most successful balloon borne telescopes, including BAM, BOOMERANG, and BLAST. Canadian researchers possess expertise in all aspects of fielding major balloon borne telescopes, including mechanical design, software, pointing systems, thermal control, communications, and power systems. The program intimately involves graduate students at all levels, producing well rounded researchers capable of significant broad contributions to the design and operation of space borne satellites. The balloon program is supported by a purpose-built high-bay facility and a thermal-vacuum environmental chamber at the University of Toronto, and the beam line at TRIUMF for testing the radiation susceptibility of flight electronics.

Industrial Expertise and Partnerships

Canadian industry has been involved with providing many aspects of presently operating CMB instruments, though the vast majority of forefront technology development has taken place at universities thus far (e.g. the readout system development described below, software development, experiment integration, etc.). This is primarily because Canadian industry typically lacks the equipment and expertise for operating sub-Kelvin cryogenic systems.

Some examples of Canadian industrial expertise include: Empire Dynamic Systems (Coquitlam, BC) who provided the mechanical design and construction for the BLAST stratospheric balloon gondola and ACT telescope in collaboration with UBC; and COM DEV (Ottawa, Ontario) who are providing the guider system from the James Webb Space Telescope, which is perhaps Canada's largest contribution to a space mission to date. COM DEV is now developing radiation fault mitigation firmware technology collaboratively with McGill for use on Field Programmable Gate Arrays (FPGAs) for satellite applications.

Building the instruments we propose here offers an opportunity to share the extensive cryogenic design and operational experience in Canadian University research groups with our industrial partners. These partnerships are already developing. Members of this DWG have built cryogenic electronics and mechanisms for space flight, have built space-flight cryostats and have worked with industry to do the same.

Opportunities

The Canadian community is at present involved in several very promising space-based cosmic microwave background experiments and it is vital that these are funded through the lifetime of the projects including the analysis phase. These experiments will further nurture a healthy Canadian CMB community and allow it to demonstrate its considerable skill. More importantly, they will yield excellent science. Funding for the full life cycle of these experiments is not established, and doing so is as important as taking a longer look ahead. Planck, the ESA all sky survey satellite, will make a dramatic step forward from WMAP in both sensitivity and angular resolution, and the Canadian effort in data analysis is crucial to that effort. EBEX (Grainger *et al.*, 2008), PIPER (A. Kogut, PI), and Spider (Crill *et al.*, 2008) are approved stratospheric balloon experiments to measure polarization of the CMB. The three programs have different technical approaches and slightly different science goals. All three have the potential to make important breakthrough measurements and all three feature Canadian experimentalists in crucial high profile roles.

EBEX and Spider will be the first generation of CMB balloon experiments using new large format bolometer arrays. One should anticipate that the success of these efforts will likely lead to another generation of suborbital experiments. The DWG believes that Canada should participate very eagerly in this process. First, these short development time experiments are an excellent incubator of both experiments and experimenters. The 13-member WMAP team had flown over 25 different balloon and sounding rocket experiments before designing and proposing the satellite, experience which allowed them to build such a well targeted mission. The WMAP papers are some of the most cited scientific results (from any scientific discipline) to date. Second, if history is a guide, these smaller experiments will yield important scientific results. This is the real reason to do them. Data from the Toco, Maxima, and Boomerang experiments established the location of the first acoustic peak of the CMB power spectrum, and from that the implication that the Universe is flat and dominated by a cosmological constant, two years before WMAP had any data. Our recommendation is best supported by a healthy CSA Small Payloads program coupled to an expanded SSEP, so a new CSA program of high profile within the LRP is not needed to accomplish these near-term goals.

The smallest satellite mission that could have a substantial impact on CMB research might cost $150 Million, which is a mission size Canada could afford to lead. To illustrate plausibility, and not to imply that the DWG prefers this option, we outline one idea which has been crudely costed using a NASA SMEX template, including launch costs. The standard approach to getting sufficient sensitivity is to couple thousands of single mode bolometers to the sky. Similar sensitivity is available more economically in a small number of multimode detectors, and a polarizing FTS coupled to small cryogenic optics and a large field of view could be made to survey the whole sky at very low angular resolution. For such a satellite to be executed economically requires a tight focus on requirements, no effort to produce ancillary science products, and a small science team. The impediment to pursuing an idea like this in Canada is the lack of a program which has ever funded a Canadian-lead space astronomy mission of this scale.

Because of the enormous anticipated scientific payoff, the world astronomical community believes that an ambitious CMB polarization satellite will follow Planck and the next generations of ground-based and sub-orbital experiments. The view of the DWG is that a launch of such a mission near to the end of the coming decade is likely, and that Canada should prepare for a partnership role in that mission. The narrowest such mission will survey the whole sky with enough sensitivity to detect a tensor to scalar ratio of r=0.01 at the large angular scales which can only be done from a satellite. A fuller mission would also work with sufficient angular resolution to see lensing and other anticipated features.

European design studies for such a mission, working under the name B-Pol (de Bernardis *et al*. 2007), have explicitly included Canadian readout electronics in the baseline plan.

In the U.S., several NASA design studies funded in the Beyond Einstein program, specifically Einstein Inflation Probe (G. Hinshaw, PI) and EPIC (J. Bock, PI), have studied options for thorough CMB polarization experiments in some detail. These missions require large optics and a large bolometer array, again using readout electronics Canadians have developed. (Both Hinshaw's lab and Bock's lab use Canadian-built electronics in their current experiments.) These missions are anticipated to be expensive. EPIC is estimated to cost $657 Million (2007 U.S.). B-Pol and EIP will cost a similar amount.

In Japan, JAXA and the KEK detector laboratory are studying a slightly smaller, entirely cryogenic mission called LiteBIRD for possible launch in 2020. The current working design includes readout electronics patterned after systems developed by Canadian teams.

Though it is very unlikely that all of these missions will be built, it is very likely that one of them will be—and that Canadian experimenters and data analysts will be welcomed enthusiastically into whichever of these missions moves forward. The DWG anticipates bringing forward a proposal in about five years time to participate as a full partner in a large international CMB polarization experiment, coming in at the start, participating in the design of the experiment, providing hardware, and analyzing the data.

Technology

Measurements of the CMB polarization with sufficient sensitivity to detect the faint curl component polarization produced by gravity waves requires a 1-2 orders of magnitude improvement in sensitivity over WMAP, together with exquisite control of systematic errors.

Contemporary mm-wave detectors are approaching the fundamental noise limit set by the intrinsic shot noise of the CMB photons themselves. As such, most design efforts have concluded that the requisite sensitivity is best achieved with large focal planes containing thousands of sensors. Other (less favored) possibilities include using fewer sensors with multi-moded optics. This viewpoint is supported by the first technology recommendation of the report of the Task Force for Cosmic Microwave Background Research, “technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors.” Key technology components for kilo-pixel arrays include (1) the ability to fabricate large arrays lithographically, (2) the ability to multiplex the cryogenic readout of these sensors, and (3) the ability to process, monitor, and interpret the data for both quasi-realtime experiment health analysis, and offline monitoring/analysis. An equally important aspect for CMB polarization experiments will be the ability to modulate the polarization signal and perform measurements with multi-band frequency coverage.

The development path that will provide and evaluate the technology necessary to accomplish these goals consists of pathfinder experiments on the ground, followed by flight demonstrations on stratospheric balloon platforms. This development path allows not just for the evaluation of whether each technology works, but perhaps equally important, how to best use each technology (for example: scan strategies, observation depth vs. width, modulation speeds, etc.).

In the sub-sections to follow, we summarize the technological readiness for each of the components listed above and discuss the role Canadians will play in the development.

Kilo-pixel Detector Arrays:

Transition Edge Sensors (TES) are the forefront detector technology. There has been tremendous development in the last 5 years. APEX-SZ (ground based) was deployed in 2006, with 300 TES bolometers. The South Pole Telescope (SPT, ground based) and Atacama Cosmology Telescope (ACT, ground based) followed soon thereafter in 2007 with a thousand or more detectors on the sky. First scientific results have recently been published by APEX-SZ and SPT, with results from ACT expected shortly. Two stratospheric balloon experiments, each with a thousand or more sensors, EBEX and SPIDER, will undergo test flights soon. If these flights are successful, large arrays of TES bolometers will have been demonstrated in a relevant flight environment, a major step toward using them on a satellite.

Canadian teams have not been involved with the construction of TES bolometer arrays. They have been instrumental in the development, implementation, and fielding of readout systems for large TES arrays (see section below). In addition, the McGill group has built a facility for the dark characterization of TES bolometer arrays. This characterization is necessary both to "tweak" the fabrication process, and for the validation of arrays before they are deployed on instruments. The SPT 2009 season TES arrays were characterized at McGill. The level of funding necessary for competitive development of TES arrays is beyond what is presently available in Canada. Several teams, all based in the USA, are building arrays at a high standard and new Canadian investment in this technology development is not necessary. The synergetic position Canadians have established with these partners through their readout electronics development places Canadians in an excellent position for collaborative development of new instruments.

TES bolometers typically operate from a bath temperature of 50-250 mK, and so flight qualified sub-Kelvin refrigeration technologies are needed. These technologies are already available and will be at TRL 9 on the time frame of a future CMB-polarization mission (e.g. the 100 mK dilution refrigerator technology being flown on Planck).

Multiplexed Cryogenic Readout Systems for TES Arrays

For large arrays of TES bolometers, constraints on complexity and heat load make it difficult to route separate leads from each bolometer to the warm readout electronics. It is necessary to multiplex the signal from many bolometers at the cold stage into a smaller number of output channels. One of the challenges in fielding a thousand or more bolometer-based polarization sensitive receivers is the development of appropriate readout technology. Canadians have been at the leading edge of this technology development.

There are presently two complimentary multiplexing technologies in use for TES detectors in the field: time division multiplexing (TDM) and frequency domain multiplexing (fMUX). Mark Halpern's group at UBC has partnered with NIST to design the room temperature backend electronics for the TDM system, and has built or is building the readout system for a number of experiments including SCUBA2, ACT, SPIDER, Clover, and others. Matt Dobbs co-led the development of the fMUX system for APEX-SZ and SPT while he was at Berkeley, and his group at McGill has developed a new digital backend electronics for the fMUX system that will be deployed on SPT-pol, POLARBEAR, and EBEX. Presently, every funded experiment that plans to measure CMB polarization with TES detectors that we know of is using readout technology from UBC or McGill. Canadians have established themselves as leaders in this technological arena. We note, also, that Barth Netterfield's group at Toronto has built non-multiplexed electronic readout systems for the BLAST sub-mm stratospheric balloon experiment, adding further flight expertise to the Canadian knowledge base.

While both TDM and fMUX systems have been demonstrated on the ground, their adaptation to a relevant flight environment is critical. Both UBC and McGill teams have been focusing development on this target, and expect to see their systems fly on stratospheric balloon test flights for SPIDER and EBEX, respectively, within the next year. The McGill team has begun to partner with an industrial partner, COM DEV, and the CSA through its Partnership Support Program, to address the issue of radiation hardness for the Field Programmable Gate Arrays (FPGAs) that perform the digital signal processing for the system.

Quasi-realtime Experiment Health Analysis, and Offline Monitoring/analysis

In order to monitor, understand, and provide the feedback necessary to improve an experiment in operation, it is necessary to rapidly monitor the data, and provide a quick analysis of a number of indicators that evaluate the health of the instrument. Barth Netterfield's group at Toronto and Douglas Scott's group at UBC have developed the "KST" software package (with funding from CSA) to provide quicklook timestream analysis, and associated code to monitor experiment health. This software has been used extensively on BLAST. It is publicly available and nearly every experiment involved in CMB research uses it in their labs and on their instruments. The Toronto and UBC groups are responsible for providing and operating the health analysis software for the Planck mission HFI and LFI instruments respectively.

Polarization Modulation and Multi-frequency Coverage

The WMAP project has demonstrated the environment of extreme stability a satellite platform can provide. Even with this stability, polarization modulation will be key in controlling systematic errors. Many strategies exist, including the simple rotation of the space-craft. Most system designs include a cryogenic half-wave plate that is continuously rotating (a stepped half-wave plate is often used as a fall-back strategy to mitigate the risk from excessive bearing wear and vibrations from the rotation). While the benefits of this strategy are well understood, the technology is not yet mature and key technological demonstrations are still needed. The Maxipol balloon-borne polarimeter (Johnson *et. al*. 2003) successfully flew a rotating half wave plate with a central drive shaft. This design was relatively small, covering 16 detectors. Larger wave-plates that are driven without the use of a central shaft are needed. They are being developed by USA collaborators for the EBEX and SPIDER experiments and will reach TRL 5 if they are successfully flown. Canadian researchers at UBC, McGill, and Toronto will be peripherally involved in the demonstration of this technology through their roles on these experiments. The McGill group has built backend readout electronics for the digitization of optical encoder data for the EBEX mission.

Polarized foregrounds will play an important role in a polarization mission addressing inflationary physics, particularly for an experiment targeting full sky coverage. Galactic polarized emission at large angular scales will likely be the largest contaminant, necessitating their accurate measurement and modeling. A factor 10 or better suppression is needed. Since the frequency spectrum of the CMB is known to high precision, a large number of frequency bands allows for the separation of signals with other spectra. The exact specification of band locations, widths, and numbers requires detailed simulations of the contamination signals. Near-term results from the first B-mode experiments (such as SPIDER and EBEX, expected in the early part of the 2010 decade) will be essential for providing the necessary input data to accurately choose bands for a satellite mission. This is one example of how the latter part of the CMB polarization roadmap builds on the earlier results.

In summary, Canadians have established themselves as international leaders in the development of readout systems for large TES bolometer arrays and software/analysis tools for instrument monitoring. This technology is being developed towards technical readiness for satellite platforms, but continued investment is necessary to reach this goal. While Canadians are not presently involved with TES detector fabrication and cryogenic half wave-plate development, they partner with world leaders in these technologies and are playing a role in its development. Through these strategic partnerships and research investments, the Canadian community is expected to have access to the technology needed for a satellite platform polarization satellite. Adequate development and funding of these technologies in ground-based and aboard stratospheric balloon platforms is essential for technological success.

Road-mapping

Over the next decade, the CMB community has embarked on a path with the goal of detecting the signature of primordial gravitational waves in the polarization of the CMB. It has a complementary program of small angular scale measurements of the CMB from the ground that is already well underway. Three projects are currently underway with strong Canadian involvement. They have a realistic chance of achieving this goal if the signal turns out to be large enough. These experiments are also the natural predecessors to an eventual CMB polarization satellite, which will have significantly better sensitivity and provide the definitive all-sky measurement of CMB polarization across the angular scales accessible to satellite platforms (larger than ~10 arcminutes). Design and construction of the 'CMBpol' satellite project will begin in earnest in the early part of the next decade (2012-2015). A road map for the decade follows.

The Planck Satellite: (timeframe - launch in 2009, analysis continuing to 2014)

Planck is an ESA led CMB satellite which is scheduled to be launched in the first half of 2009, with a primary mission which will extend to 2011. This satellite will map the entire sky in both temperature and polarization. Planck will be cosmic variance limited in the temperature spectrum of the CMB down to several arc-minute scales, and will measure the CMB polarization to high accuracy over the whole sky. With multi-frequency polarized photometers, Planck will additionally learn an enormous amount about the nature of the polarized foregrounds, and will measure the polarization signal due to gravitational lensing from clustered matter in the Universe. These things will be the eventual limit of measurements of the CMB. In terms of raw sensitivity, Planck has the potential to achieve our main science goals.

However, Planck was not designed as a polarimeter, and there are some serious concerns that Planck's control of systematic errors, including understanding the polarized beam, and spectral band-passes may eventually place a significant limit on the precision of Planck's final result. Over the next decade, members of the Canadian CMB community will be actively involved in the analysis of Planck data, focusing on these issues, bringing to bear measurements from other past and current experiments we are involved with, and extending the lessons learned with Planck towards the design of a 'CMBpol' satellite.

The EBEX balloon borne CMB experiment: (timeframe - flights in 2009-2011, analysis continuing to 2014)

EBEX is a balloon borne mm-wave experiment designed to measure the polarization of the CMB with approximately the same resolution and spectral coverage as Planck. Unlike Planck, however, EBEX has been designed as a polarimeter from the beginning, and utilizes a rotating wave-plate to modulate polarization, reducing beam and band-pass variation with polarization angle over what will be achieved by Planck. EBEX will observe a smaller region of the sky than Planck, giving it more sensitivity per pixel, which improves EBEX's ability to remove foregrounds. EBEX will choose a section of the sky known to be relatively free of galactic foregrounds. Like Planck, EBEX will be able to measure the polarization from clustered matter in the Universe.

Amongst the challenges for EBEX, however, will be its ability to determine its beam shape with respect to polarization angle, which may ultimately limit its ability to distinguish the signature of gravitational waves.

EBEX is scheduled to make its test flight in 2009, with its first science flight to follow in 2010 or 2011. As a balloon borne experiment, EBEX provides an opportunity to make multiple flights building on lessons from previous flights, making EBEX a fantastic test bed for one of the proposed approaches to an eventual CMB polarization satellite.

The Spider balloon borne CMB experiment: (timeframe - flights in 2010-2012, analysis continuing to 2015)

Spider is a balloon borne mm-wave experiment designed to measure the polarization of the CMB with similar spectral resolution as Planck and EBEX, but with much lower angular resolution. In this regard, it is more like the low-cost version of the CMBpol satellite being considered in the NASA Mission Concept Study (CMBpol, 2009). Spider has been designed from the beginning to minimize systematic effects and maximize overall sensitivity on large angular scales, where the signature of primordial gravitational waves is largest, but loses any ability to probe smaller angular scales. Spider has proposed two major science flights: one to map half of the sky with moderately better sensitive than Planck, and one to map ~8% of the sky with significantly better sensitivity per pixel than Planck. Spider's design is intended to have lower instrumental systematics than either Planck or EBEX.

However, Spider also faces challenges. The approach of a large post-optics wave-plate has not been proven, and Spider is unable to determine the amplitude of the lensed CMB signal which may eventually limit future experiments on large scales.

Spider is scheduled for a test flight in early 2010, and a first science flight in 2011 or 2012. Like EBEX, as a balloon-borne experiment, Spider can be flown multiple times should it prove valuable to refine the approach, again making it the ideal test-bed for the other major proposed architectures of an eventual CMB polarization satellite.

CMB Polarization Satellite: (timeframe - begin 2012-2015, launch in the latter half of the decade)

Following the current missions, the Canadian CMB community intends to be engaged in a next-generation CMB polarization satellite, whose science goal will be the detection and characterization of the signature of primordial gravitational waves through measurements of the polarization of the CMB. The detailed design of the experiment is not yet possible, however, due to significant uncertainties regarding the nature of the foregrounds, or the efficacy of the three very different strategies being pursued by Planck, EBEX, and Spider.

Two major classes of instruments are being considered: a large aperture telescope, as being explored by EBEX, which will be capable of probing the polarization signature due to gravitational lensing by dark matter, as well as the primordial gravitational waves, and a small aperture telescope, as being explored by Spider, which sacrifices resolution for lower cost and easier control of systematics. Which approach, if either, is better can not currently be decided, as the nature of the foregrounds, the efficacy of the various schemes at controlling systematics, and the amplitude of the signal to be explored are not well understood.

Results from Planck, EBEX, and Spider will provide invaluable insights into the appropriate design of the Satellite. Design work for a 'CMBpol' experiment will begin in earnest in the early part of the next decade (2012-2015), when these results are known. The mission will likely be an international collaboration. With the experience gained in the current generation of missions, we plan to play a significant role in this very exciting mission.

Technology Development: (timeframe - immediate)

Successful technology development is the necessary ingredient for these missions. Canadian's success in this arena (both in terms of hardware and software/analysis technology) has defined our international reputation of excellence and made possible our many collaborations. Support for technology development, which may be best supported through an enhanced CSA SSEP program, is necessary for excellence in CMB science over the next decade.

Training of HQP: (timeframe - immediate)

The Canadian community already has strong leadership and internationally recognized expertise. This community requires additional, stable, long term resources to support the training of highly qualified personnel. An NSERC CREATE-like program, providing graduate student and postdoc stipends, as well as technical staff may be a natural strategy for this. Presently, the community in Canada supports itself with project grants that lack continuity and typically provide little support for long term technology development. A CSA-funded CREATE-like program administered through a revamped Grants and Contributions program would address this. We note that within this program, the center should have freedom to use funding to support technical staff/trainees as well as academic trainees.

Recommendations and Conclusions

The Cosmic Microwave Background Working Group anticipates that there will be one or two more generations of sub-orbital and custom ground-based experiments leading to a major mission to map the polarization of the CMB over the whole sky with sufficient angular resolution to study the gravitational lensing signal and with sensitivity at least an order of magnitude better than any currently designed experiment. This program will either resolve our questions about how inflation ended or will set such stringent limits on CMB polarization patterns that our current models of how the Universe began and came to be so large and full of structure will be seriously threatened.

This pattern of several generations of sub-orbital experiments producing important results followed by definitive measurements from a satellite has served the field very well through COBE, WMAP and we anticipate Planck. We expect this very productive cycle to continue.

The Canadian CMB community is vibrant and well recognized. It leads the world in a number of key technologies and analysis techniques, and has an enviable record of success on flight missions. This success should be fostered. There are a few very talented post docs in the current generation of experiments and we believe this presents an excellent opportunity to grow the Canadian CMB community if a way can be found to help universities hire in these uncertain times.

The recommendations of the CMB working group are:

- To continue to fund sub-orbital projects on merit through the CSA Small Missions, or a similar program. The community and the CSA should anticipate another generation of CMB experiments after the currently funded set.
- To fund missions for their full lifetime, including data analysis, as long as they demonstrate through periodic review that they are scientifically productive. This is especially important for Planck, but it is important for all CMB missions. An expanded SSEP-style for funding post-doctoral fellows would suffice, providing adequate funding is made available.
- Provide a continuity of funding for technology development and training of highly qualified personnel through a new, CREATE-like program. Fund technology development within the SSEP program.
- To fund participation as a full partner in an international effort to build a mission which will produce ambitious full sky polarization maps of the CMB. The Working Group will be active in the CASCA Long Range Planning exercise to assure that there is broad community support for this mission.

We have found the meetings held as part of the CSA DWG process to be very beneficial.* This is especially true of our first planning meeting, in which graduate students and Post Docs were pushed to imagine that their current efforts succeed and articulate what comes next. We would like to hold a meeting of this sort every second year.

* We found the bureaucracy regarding the administration of the DWG contract onerous, and not an effective use of time considering the scale of funding. A program like the DWG may be better funded by grants and contributions, and rules and regulations regarding travel need to be clearly spelled out well in advance.

References

A. Albrecht and P. J. Steinhardt "Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking", Phys. Rev. Lett., 48:1220–1223, 1982.

J. Aguirre et al., "Observing the Evolution of the Universe" FERMILAB-PUB-09-075-A, Mar 2009. e-Print: arXiv:0903.0902 White Paper for the 2010 U.S. Decadal survey.

P. de Bernardis *et al.*, "A B-Polarization Satellite for Detecting Primordial Gravitational Waves from Inflation", http://www.orangecoffee.it/bpol/index.php, proposal for phase A study submitted to the 2007 ESA Cosmic Visions.

R. Weiss (Chair), J. Bock, S. Church, M. Devlin, G. Hinshaw, A. Lange, A. Lee, L. Page, B. Partridge, J. Ruhl, M. Tegmark, P. Timbie, B. Winstein, and M. Zaldarriaga, "Report of the Task Force on CMB Research (TFCR) as a joint subcommittee to advise NSF, NASA, and DOE on the future of research on the polarization of the cosmic microwave background", ArXiv Astrophysics e-prints, Apr. 2006. URL http://arxiv.org/abs/astro-ph/0604101 and http://www.nsf.gov/mps/ast/tfcr.jsp .

J. Bock, A. Cooray, S. Hanany, B. Keating, A. Lee, T. Matsumura, M. Milligan, N. Ponthieu, T. Renbarger, and H. Tran. "The Experimental Probe of Inflationary Cosmology (EPIC): A Mission Concept Study for NASA's Einstein Inflation Probe" ArXiv e-prints, May 2008. URL http://cmbpol.uchicago.edu/depot/pdf/epic-report.pdf.

CMBpol Mission Concept Study Report for the Astro2010 Decadal Committee on Astrophysics, (authors and endorsers are too many to list), Edited by S. Meyer and S. Hanany, to appear April 2009, http://cmbpol.uchicago.edu.

B. P. Crill, P. A. R. Ade, E. S. Battistelli, S. Benton, R. Bihary, J. J. Bock, J. R. Bond, J. Brevik, S. Bryan, C. R. Contaldi, O. Dor´e, M. Farhang, L. Fissel, S. R. Golwala, M. Halpern, G. Hilton, W. Holmes, V. V. Hristov, K. Irwin, W. C. Jones, C. L. Kuo, A. E. Lange, C. Lawrie, C. J. MacTavish, T. G. Martin, P. Mason, T. E. Montroy, C. B. Netterfield, E. Pascale, D. Riley, J. E. Ruhl, M. C. Runyan, A. Trangsrud, C. Tucker, A. Turner, M. Viero, and D. Wiebe. SPIDER: a balloon-borne large-scale CMB polarimeter. In Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, volume 7010 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Aug. 2008. doi: 10.1117/12.787446.

R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T.Wilkinson. Cosmic Black-Body Radiation. ApJ, 142:414–419, 1965.

M. Dobbs and A. Lee, "MHz Frequency Domain Multiplexed Readout", CMBpol Instrument Technologies Whitepaper, 2008, http://cmbpol.uchicago.edu/workshops/technology2008/depot/dobbs_dfmux_20080714.pdf .

M. Dobbs, N. W. Halverson, P. A. R. Ade, K. Basu, A. Beelen, F. Bertoldi, C. Cohalan, H. M. Cho, R. G¨usten, W. L. Holzapfel, Z. Kermish, R. Kneissl, A. Kov´acs, E. Kreysa, T. M. Lanting, A. T. Lee, M. Lueker, J. Mehl, K. M. Menten, D. Muders, M. Nord, T. Plagge, P. L. Richards, P. Schilke, D. Schwan, H. Spieler, A. Weiss, and M. White. APEX-SZ first light and instrument status. New Astronomy Review, 50:960–968, Dec. 2006. doi: 10.1016/j.newar.2006.09.029.

S. Dodelson *et al.*, "The Origin of the Universe as Revealed Through the Polarization of the Cosmic Microwave Background" FERMILAB-PUB-09-052-A, Feb 2009. e-Print: arXiv:0902.3796 White Paper for the 2010 U.S. Decadal survey.

Grainger, Will; Aboobaker, Asad M.; Ade, Peter; Aubin, François; Baccigalupi, Carlo; Bissonnette, Éric; Borrill, Julian; Dobbs, Matt; Hanany, Shaul; Hogen-Chin, Clayton; Hubmayr, Johannes; Jaffe, Andrew; Johnson, Bradley; Jones, Terry; Klein, Jeff; Korotkov, Andrei; Leach, Sam; Lee, Adrian; Levinson, Lorne;Limon, Michele; Macaluso, John; MacDermid, Kevin; Matsumura, Tomotake; Meng, Xiaofan; Miller, Amber; Milligan, Michael; Pascale, Enzo; Polsgrove, Dan;Ponthieu, Nicolas; Reichborn-Kjennerud, Britt; Renbarger, Tom; Sagiv, Ilan; Stivoli, Federico; Stompor, Radek; Tran, Huan; Tucker, Greg; Vinokurov, Jerry;Zaldarriaga, Matias; Zilic, Kyle, "EBEX: the E and B Experiment", Millimeter and Submillimeter Detectors for Astronomy, Proc. of SPIE, Vol. 7020 (2008) 70202N-70202N-9.

A. H. Guth. The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems. Phys. Rev., D23:347–356, 1981. doi: 10.1103/PhysRevD.23.347.

G. Hinshaw, J. L. Weiland, R. S. Hill, N. Odegard, D. Larson, C. L. Bennett, J. Dunkley, B. Gold, M. R. Greason, N. Jarosik, E. Komatsu, M. R. Nolta, L. Page, D. N. Spergel, E. Wollack, M. Halpern, A. Kogut, M. Limon, S. S. Meyer, G. S. Tucker, and E. L. Wright. Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Data Processing, Sky Maps, and Basic Results. ArXiv e-prints, 803, Mar. 2008. Astrophys.J.Suppl.180:225-245,2009 [arXiv:0803.0732].

K. Irwin and M. Halpern, "Time-Division SQUID Multiplexers", CMBpol Instrument Technologies Whitepaper, 2008, http://cmbpol.uchicago.edu/workshops/technology2008/depot/tdm_white_paper_v1.pdf .

B.R. Johnson et. al., "MAXIPOL: a balloon-borne experiment for measuring the polarization anisotropy of the cosmic microwave background radiation", New Astronomy Reviews, Volume 47 (2003) 1067-1075.

E. Komatsu *et al.*, "Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation" 2009, ApJS, 180, 330-376.

A. Kosowsky. The Atacama Cosmology Telescope Project: A Progress Report. New Astron. Rev., 50:969–976, 2006.

A. D. Linde. A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems. Phys. Lett., B108:389–393, 1982.

J. Ruhl, P. A. R. Ade, J. E. Carlstrom, H.-M. Cho, T. Crawford, M. Dobbs, C. H. Greer, N. Halverson,W. L. Holzapfel, T. M. Lanting, A. T. Lee, E. M. Leitch, J. Leong,W. Lu, M. Lueker, J. Mehl, S. S. Meyer, J. J. Mohr, S. Padin, T. Plagge, C. Pryke, M. C. Runyan, D. Schwan, M. K. Sharp, H. Spieler, Z. Staniszewski, and A. A. Stark. The south pole telescope. volume 5498, pages 11–29. SPIE, 2004. doi: 10.1117/12.552473.

G. F. Smoot, C. L. Bennett, A. Kogut, E. L. Wright, J. Aymon, N. W. Boggess, E. S. Cheng, G. de Amici, S. Gulkis, M. G. Hauser, G. Hinshaw, P. D. Jackson, M. Janssen, E. Kaita, T. Kelsall, P. Keegstra, C. Lineweaver, K. Loewenstein, P. Lubin, J. Mather, S. S. Meyer, S. H. Moseley, T. Murdock, L. Rokke, R. F. Silverberg, L. Tenorio, R. Weiss, and D. T. Wilkinson. Structure in the COBE differential microwave radiometer first-year maps. ApJL, 396:L1–L5, Sept. 1992. doi: 10.1086/186504.

Appendix A: Working Group Membership

One of the great strengths of this DWG effort has been active participation at all seniority levels. Graduate students, postdocs, and faculty members have all had the opportunity to learn from one another, develop their ideas together, and contribute to the formation of the roadmap for this field.

Faculty members:

- Matt Dobbs (McGill University) DWG Chair <Matt.Dobbs@McGill.ca>
- Dick Bond (U. Toronto/CITA) <bond@cita.utoronto.ca>
- Mark Halpern (UBC) <halpern@physics.ubc.ca>
- Gil Holder (McGill University) <holder@hep.physics.mcgill.ca>
- Barth Netterfield (U. Toronto) <netterfield@astro.utoronto.ca>
- Ue-Li Pen (Faculty, CITA/U. Toronto) <pen@cita.utoronto.ca>
- Dmitri Pogosyan (U. Alberta) <pogosyan@phys.ualberta.ca>
- Douglas Scott (UBC) <dscott@astro.ubc.ca>

Postdoc and Non-tenured Researcher Members

- Olivier Dore (Research Associate, CITA) <olivier@cita.utoronto.ca>
- Peter Hyland (Postdoc, McGill) <peter.o.hyland@gmail.com>
- Gaelen Marsden (Postdoc, UBC) <gmarsden@physics.ubc.ca>
- Adam Moss (Postdoc, UBC) <adammoss@phas.ubc.ca>
- Michael Nolta (Research Associate, CITA) <nolta@cita.utoronto.ca>
- Laurie Shaw (Postdoc, McGill) <lds@physics.mcgill.ca>
- Jonathan Sievers (Research Associate, CITA) <sievers@cita.utoronto.ca>

Graduate Student Members

- Francois Aubin (Graduate Student, McGill) <francois.aubin@mail.mcgill.ca>
- Steve Benton (Graduate Student, U. Toronto) <steve.benton@utoronto.ca>
- Peter Dahlberg (Undergraduate Student, McGill) <peter.dahlberg@mail.mcgill.ca>
- Tijmen de Haan (Undergraduate Student, McGill) <tijmen.dehaan@mail.mcgill.ca>
- John Dudley (Graduate Student, McGill) <dudleyj@physics.mcgill.ca>
- Alex Van Engelen (Graduate Student, McGill) <engelen@physics.mcgill.ca>
- Marzieh Farhang (Graduate Student, U. Toronto) <farhang@astro.utoronto.ca>
- Laura Fissel (Graduate Student, U. Toronto) <fissel@astro.utoronto.ca>
- Joachim Harnois (Graduate Student, U. Toronto) <jharno@cita.utoronto.ca>
- Matt Hasselfield (Graduate Student, UBC) <mhasse@physics.ubc.ca>
- James Kennedy (Graduate Student, McGill) <james.kennedy2@mail.mcgill.ca>
- Kevin MacDermid (Graduate Student, McGill) <kevin.macdermid@mail.mcgill.ca>
- Marco Viero (Graduate Student, U. Toronto) <viero@astro.utoronto.ca>
- Don Wiebe (Graduate Student, U. Toronto) <dwiebe@physics.utoronto.ca>

- Wan Yan Wong (Graduate Student, UBC) <wanyan@phas.ubc.ca>

Former members:

- Brendan Crill was a (non-tenured) faculty member at U. Toronto. He was a DWG member until he moved on to a staff scientist position (working on the Planck CMB polarization satellite) at Caltech in 2008.
- Colin Borys was a CSA Fellow and (non-tenured) faculty member at U. Toronto. He was a DWG member until he moved on to a staff scientist position at Caltech in 2007.

Addresses:

- U. Alberta is: Department of Physics, 11322 - 89 Avenue, University of Alberta, Edmonton, AB T6G 2G7
- UBC is: Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road Vancouver, B.C. V6T 1Z1
- CITA is: The Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George St., Toronto, ON M5S 3H8
- McGill University is: Department of Physics, McGill University, 3600 University Street, Montreal, QC H3A 2T8
- U. Toronto is: Department of Physics, University of Toronto, 60 St. George St., Toronto, ON M5S 1A7

Appendix B1: Report of February 2009 Meeting

A one-day focused meeting was hosted by the University of Toronto in their Balloon Flight Facility. Senior (faculty level) members of the working group and representatives from the postdoc community were invited. The primary goal of this meeting was to agree on scientific priorities for the Canadian CMB community, identify opportunities, and formulate a roadmap for this community that is commiserate with the strengths in Canada and national capabilities.

Attendees of the meeting were:

Matt Dobbs (Faculty, McGill University)
Dick Bond (Faculty, U. Toronto/CITA)
Mark Halpern (Faculty, UBC)
Barth Netterfield (Faculty, U. Toronto)
Dmitri Pogosyan (Faculty, U. Alberta - by telephone)
Douglas Scott (Faculty, UBC)
Michael Nolta (Research Associate, CITA)
Jonathan Sievers (Research Associate, CITA)

The only senior (faculty level) member of the working group who was not able to attend was Gil Holder (McGill University), due to prior commitments.

Appendix B2: Report for March 2008 Workshop/Meeting

(appended)

McGill University Physics Department, 3600 Rue Université, Montréal, Canada H3A 2T8

April 22, 2008

RE: Meeting Summary for the Cosmic Microwave Background DWG

Dear Dr. David Kendall (CSA Director General of Space Science),

The CSA funded CMB discipline working group met for a 4 day workshop hosted by McGill University in Montreal. Our goals were three fold: (1) study and understand prospects for future space astronomy measurements of the CMB, (2) contribute to the training of highly qualified personnel by dedicating time and resources to expert lectures covering the science and instruments, (3) provide a forum for interactions and discussions on present technology and data reduction/analysis techniques and new results from experiments with direct Canadian involvement.

The webpage outlining the agenda and topics is attached as an appendix to this report. It is available online at: http://kingspeak.physics.mcgill.ca/twiki/bin/view/Main/CMB-CanadaWorkshop2008?cover=print.pattern . Copies of slides from all talks are linked from this webpage.

The attendance for the workshop greatly exceeded expectations. We anticipated 15-20 participants and ~40 people attended (including many international participants, who paid all of their own expenses). We were able to obtain matching funding from McGill University and CIfAR to support the workshop.

Attendees of the meeting were:

- Francois Aubin (Graduate Student, McGill)
- Amy Bender (Graduate Student, U. Colorado) – not a member of the DWG
- Steve Benton (Graduate Student, U. Toronto)
- Brendan Crill (Faculty, U. Toronto)
- Matt Dobbs (Faculty, McGill)
- Olivier Dore (Research Associate, CITA)
- John Dudley (Graduate Student, McGill)
- Alex Van Engelen (Graduate Student, McGill)
- Marzieh Farhang (Graduate Student, U. Toronto)
- Laura Fissel (Graduate Student, U. Toronto)
- Mark Halpern (Faculty, UBC)
- Joachim Harnois (Graduate Student, U. Toronto)
- Matt Hasselfield (Graduate Student, UBC)
- Gil Holder (Faculty, McGill)
- Peter Hyland (Postdoc, McGill)
- James Kennedy (Graduate Student, McGill)
- John Macaluso (Graduate Student, Brown University) – not a member of the DWG
- Gaelen Marsden (Postdoc, UBC)
- Michael Milligan (Graduate Student, U. Minnesota) – not a member of the DWG
- Marc-Antoine Miville-Deschenes (Research Associate, CITA and Faculty, Paris) – not a member of the DWG

- Adam Moss (Postdoc, UBC)
- Ue-Li Pen (Faculty, CITA/U. Toronto)
- Jeff Peterson (Faculty, Carnegie Mellon) – not a member of the DWG
- Dmitri Pogosyan (Faculty, U. Alberta)
- Barth Netterfield (Faculty, U. Toronto)
- Laura Newburgh (Graduate Student, Columbia University) – not a member of the DWG
- Michael Nolta (Research Associate, CITA)
- Britt Reichborn-Kjennerud
- Douglas Scott (Faculty, UBC)
- Kathryn Schaffer (Postdoc, U. Chicago) – not a member of the DWG
- Laurie Shaw (Postdoc, McGill)
- Jonathan Sievers (Research Associate, CITA)
- Marco Vireo (Research Associate, CITA)
- Joaquin Vieira (Graduate Student, U. Chicago) – not a member of the DWG
- Jerry Vinokurov (Graduate Student, Brown University) – not a member of the DWG
- Don Wiebe (Graduate Student, U. Toronto)

Members of the working group who were not able to attend the meeting included:
- Dick Bond (Faculty at CITA & U. Toronto)

As you can see, we had a tremendous turnout – highlighting just how important this topic is for Canadian Space Astronomy.

While the Canadian CMB space astronomy community is still studying the topic with this DWG as its vehicles, our preliminary consensus after this workshop were:

1. Measurements of the Cosmic Microwave Background (CMB) are arguable ***the*** cornerstone observations that provide the foundation of the standard cosmological model. Canadian instrument builders, data analysts, and theorists have distinguished themselves well beyond their means on the international scene—particularly in space astronomy.
2. With results from the WMAP experiment available (the papers from WMAP are the most cited scientific results in history by most metrics) and the Planck mission set to launch soon, we feel that it is premature to begin work or detailed planning for the next generation CMB satellite experiment.
3. The most important priority for the Canadian CMB Space Astronomy community is the successful design, construction, and flight of the stratospheric balloon missions that will demonstrate technology for future satellite missions and make the first important measurements or place upper bounds on the signal of inflationary gravity waves that is imprinted in the polarization of the Cosmic Microwave Background.
4. The results (both in terms of technology proof-of-concept and science measurements) of these next generation CMB polarization stratospheric balloon missions (EBEX and SPIDER) will be crucial for defining a (post-Planck) CMB satellite.
    - These balloon missions have an excellent chance of glimpsing the inflationary gravity wave signal—guiding the optimization of a future satellite.
    - Technology for a future satellite will very likely include large (>1000s) arrays of bolometric sensors such as those being flown on the balloon missions. It is crucial to

test and optimize these systems in the stratospheric ballooning environment as a stepping stone towards space deployment.

5. In order to define a next-generation (post-Planck) CMB satellite, we need to understand how well Planck is able to fulfill its polarization measurement goals at very large and very small angular scales. The capabilities of Planck in this context are widely debated, as Planck was not originally designed with CMB polarization measurements as its primary goal. With early Planck data, it is necessary to answer the following:
    a. Can Planck control its systematics well enough to make large angular scale, all sky polarization measurements at ell<12 ?? (this is the scale that needs to be well measured for the reionization signature)
    b. Can Planck control systematics (i.e. measure its polarization beams well enough and measure/subtract foregrounds) at small angular scales?

    The answers to these questions will define the angular scales that would be targeted by a future post-Planck mission.

The working group will continue its work throughout the 2008/9 year.

Sincerely,

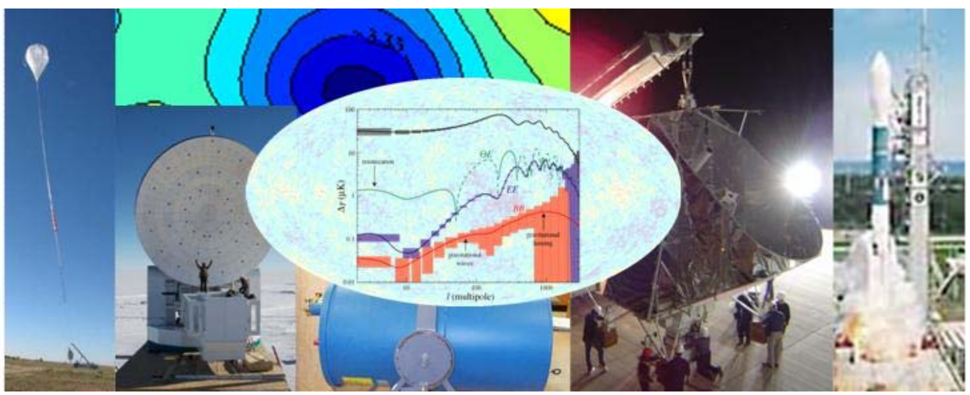
Prof. Matt Dobbs <Matt.Dobbs@McGill.ca>
Chair of the Cosmic Microwave Background DWG
Canada Research Chair in Astro-particle Physics
CIfAR Scholar
Department of Physics, McGill University
Ernest Rutherford Physics Building
3600 Rue Université
Montréal, Québec
Canada H3A 2T8

APPENDIX: Webpage Outlining Workshop Agenda

McGill

2008 Workshop and Winter School on Cosmic Microwave Background Observations

- Winterschool Day 1 Schedule
- Scientific Talks Schedule
- Winterschool Day 2 Schedule
- Meeting of the CSA Discipline Working Group
- How to register
  - Confirmed Participants
- Conference Locations



A Canada-wide (+ international friends) CMB community workshop will take place from March 27-30, 2008 at McGill University in Montreal. The workshop is hosted by the McGill Cosmology Group as part of the Canadian Space Agency CMB

Discipline Working Group (CMB-DWG, funded by the Canadian Space Agency).

Scientific Contacts: Matt Dobbs (Matt.Dobbs *at* mcgill.ca) or Gil Holder (holder *at* physics.mcgill.ca)
Hospitality Contact: Elizabeth Shearon (Elizabeth.Shearon *at* mcgill.ca)

We thank the Canadian Space Agency, the Canadian Institute for Advanced Research (CIfAR), McGill Department of Physics, and McGill Faculty of Science for financially supporting this activity.

Winterschool Day 1 Schedule

Thursday March 27, 2008

LOCATION: Leacock Building Room 232, McGill Campus (see map at bottom of page)

8:30am	registration opens. Coffee and pastries served.		
9am-10:00	CMB + Polarization Theory	Douglas Scott	CMB_TheoryIntro_DouglasScott.pdf
10:20-11:20	CMB Secondaries and Foregrounds	Gil Holder	CMB_Foregrounds_GHolder.pdf
11:40-12:40	Calculating CMB Power spectrum	Adam Moss	CMB_Parameters_AdamMoss.pdf
1pm - 2pm	lunch		
2:00-2:30pm	ACT	Mark Halpern	ACT_MarkHalpern.pdf
2:30-3:30pm	SPIDER	Barth Netterfield	
3:30-4:30	Interferometry	Jon Sievers	Interferometry_JonSievers.pdf
6:30pm	Welcome Dinner at Bistro Justine (30 persons)		

Each lecture has been allotted 1 hour. This is the formal lecture time. 20-30 minutes is available immediately after each lecture for discussion. We STRONGLY encourage lecturers not to go beyond their allotted hour, as the discussion time is the most fun.

Directions to dinner:

- On foot (30 minute walk - print the map at the bottom of the page) - take Prince Arthur East 15 minutes until you dead-end in a park. Cross the park and turn left (North) on St. Denis. Walk 15 minutes to 4517 rue Saint-Denis.
- By taxi (reduce your foot print by sharing with others please!). Walk east out of rutherford and grad a taxi on University street (there is a taxi stand one block north on university). It will cost about $10 and take 10 min.

Scientific Talks Schedule

Friday March 28, 2008

LOCATION: Rutherford Physics Building, Bell Conference Room 103, McGill Campus (see map at bottom of page)

Preliminary Agenda

9:15am	The South Pole Telescope Status (25+5)	Kathryn Miknaitis (Chicago)	SPT_KSchaffer.pdf
9:45am	Cluster detection in simulated SZ sky surveys (20+5)	Laurie Shaw (McGill)	SZ-Detections_LShaw.pdf
10:15am	CMB Lensing (20+5)	Ue-Li Pen (Toronto)	CMB_Lensing_UeLiPen.pptx
10:45am	Coffee		
11:15am	EBEX instrument (20+5)	Michael Milligan (Minnesota)	EBEX_MMilligan.pdf
11:45pm	The BLAST Instrument and Results (25+5)	Don Wiebe (UBC)	Blast_DonWiebe.pdf
12:15	LUNCH		
1pm	Design of WMAP (1hr)	Mark Halpern (UBC)	WMAP_Design-MHalpern.pdf
2:00pm	New Results from WMAP (40+5)	Michael Nolta (CITA)	WMap5_MNolta.pdf
2:45	Separation of synchrotron	Marc-Antoine	WMAP_ForegroundReconstruction_MA_Miville-Deschenes.pdf

	and anomalous emission using WMAP polarisation data (15+5)	Miville-Deschênes (Paris)	
3:05pm	coffee		
3:25	Status of the Planck Surveyor, Seven Months before Launch (25+5)	Brendan Crill (Toronto)	Planck_BrendanCrill.pdf
3:55pm	Millimeter Bolometer Interferometer (15min+5)	Peter Hyland (Wisconsin, McGill)	MBI_PeterHyland.pdf
4:15pm	Cosmology with the 21 cm Line 25+5	Ue-Li Pen / Jeff Peterson	21cm_JPeterson.pdf
5pm	CMB Polarization from Space Discussion, Adjourn		

6-8pm	Dinner at McGill Faculty Club Gold Room**	3450 MacTavish Street, McGill Campus
-9pm	Entertainment at McGill's two dimensional scattering facilities	3rd floor of faculty club

Directions to dinner:

- Walk 5 minutes to 3450 MacTavish Street on the west side of Campus. Dinner will be served in a private room on the second floor. Two dimensional scattering facilities are on the third floor.

Winterschool Day 2 Schedule

Saturday March 29, 2008

LOCATION: Rutherford Physics Building, Bell Conference Room 103, McGill Campus (see map at bottom of page)

9am-10:00	CMB Obvervations on Balloon and satellite platforms	Barth Netterfield	Ballooning_Netterfield.pdf

10:15-11:15	Bolometers and readout	Matt Dobbs	BolosReadout_Dobbs.pdf
11:30-12:30	Simulating the mm-wavelength sky and experiments	Brendan Crill	CmbSimulation_BrendanCrill.pdf
1pm - 2pm	lunch		
2:00-3pm	Data Analysis: from timestreams to maps	Olivier Dore	TimesteamsToMaps_OlivierDore.pdf
3:30-4:30	Data Analysis: the cosmo parameters and the numerology of the universe	Michael Nolta	FromMapsToParameters_MNolta.pdf
4:30pm	CMB polarimetry from Space discussion	all	
6pm-	Dinner on your own, for suggestions see MontrealLocalInfo		

- The best restaurants in Montreal all require reservations - don't forget to call ahead.

Meeting of the CSA Discipline Working Group

Sunday March 30, 2008 9am - 1pm *(all participants are welcome and encouraged to attend)*

LOCATION: Rutherford Physics Building, Bell Conference Room 103, McGill Campus (see map at bottom of page)

Discussion of requirements for space platform CMB-polarization mission and Canadian expertise (Moderated by M. Halpern & B. Netterfield)

Lunch is on your own.

How to register

Registration is now closed - sorry, we're oversubscribed and can't accept any additional attendees.

Confirmed Participants

Name,	Role	Dates attending	
Francois Aubin, francois.aubin mail.mcgill.ca	GS, McGill	Mar 27-30	local
Amy Bender, amy.bender colorado.edu	GS, Colorado	Mar 26-30	no grant, please book hotel with female roommate
Steve Benton, steve.benton utoronto.ca	GS, Netterfield	Mar 26-30	travel grant, any roommate
Ed Chapin, echapin phas.ubc.ca	postdoc, UBC	Mar 26-30	withdrawn
Brendan Crill, crill astro.utoronto.ca	faculty, Toronto	?	
Matt Dobbs, Matt.Dobbs mcgill.ca	faculty, McGill	Mar 27-30	local
Olivier Dore, olivier cita.utoronto.ca	RA, CITA	arrive early on the 27th and leave on the 29th at night	travel grant, no roommate
John Dudley, dudleyj physics.mcgill.ca	GS, Holder	Mar 27-30	local
Alex Van Engelen, engelen physics.mcgill.ca	GS, Holder	Mar 27-30	local
Marzieh Farhang, farhang astro.utoronto.ca	GS, Netterfield	Mar 26-30	travel grant, no roommate
Laura Fissel, fissel astro.utoronto.ca	GS, Netterfield?	Mar 26-30	travel grant, share with Wong
Mark Halpern, halpern physics.ubc.ca	faculty, UBC	?	
Joachim Harnois-Deraps, jharno cita.utoronto.ca	GS, Pen	Mar 26-30	travel grant, no hotel
Matt Hasselfield, mhasse physics.ubc.ca	GS, Halpern	Mar 26-30	travel grant, share with Marsden
Gil Holder, holder physics.mcgill.ca	faculty, McGill	Mar 27,28 only	local
Peter Hyland, pohyland wisc.edu	Postdoc, Dobbs	Mar 27-30	travel grant, no roommate
James Kennedy, james.kennedy2 mail.mcgill.ca	GS, McGill	Mar 27-30	local

Denis Laurin, Denis.Laurin space.gc.ca	program sci, CSA	Mar 27-30	no hotel
John Macaluso, John_Macaluso brown.edu	GS, Brown U	Mar 26-30	no travel grant, no hotel
Kevin MacDermid, kevin.macdermid mail.mcgill.ca	GS, McGill	Mar 27-28	local
Gaelen Marsden, gmarsden physics.ubc.ca	postdoc, UBC	~Mar 26-30	travel grant, share with Hasselfield
Michael Milligan, mmilligan astro.umn.edu	GS, Minnesota	~Mar 26-30	no travel grant
Marc-Antoine Miville-Deschenes, marc-antoine.miville-deschenes ias.u-psud.fr	RA, Paris	~Mar 26-30	no hotel
Adam Moss, adammoss phas.ubc.ca	postdoc, UBC	?	travel grant, no roommate
Ue-Li Pen, pen cita.utoronto.ca	faculty, CITA	Mar 28-29	please book hotel
Jeff Peterson, jeffreyb.peterson gmail.com	faculty, Carnegie Melon	Mar 28,30	please book hotel
Dmitri Pogosyan pogosyan phys.ualberta.ca	faculty, alberta	27-30	
Laura Newburgh, newburgh phys.columbia.edu	GS, Columbia	Mar 26-30	no grant, do not book hotel
Barth Netterfield, netterfield astro.utoronto.ca	faculty, Toronto	?	
Michael Nolta, nolta cita.utoronto.ca	RA, CITA	?	travel grant, no roommate
Britt Reichborn-Kjennerud, britt phys.columbia.edu	GS, Columbia Miller	Mar 26-30	no grant, please book hotel to share w/ Newburgh
Douglas Scott dscott astro.ubc.ca	faculty, UBC	?	need to reconfirm
Kathryn Schaffer, kksm kicp.uchicago.edu	postdoc, U Chicago	~Mar 26-30	no travel grant, hotel?