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EXPERIMENTAL COSMIC MICROWAVE BACKGROUND RESEARCH IN CANADA WHITEPAPER FOR THE CANADIAN DECADAL LRP

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ABSTRACT

The cosmic microwave background (CMB) is a cornerstone for precision cosmology and Canadian experimeters have been involved with the majority of significant results over the last decade. In this whitepaper, highlights from this period are presented along with a summary of our unique capabilities. With the temperature anisotropies accurately characterized out to moderate angular scales ($\ell < 700$) the community is focused on (1) small angular scale temperature anisotropy measurements to study the intervening matter through CMB secondaries and (2) the CMB polarization onto which the signature of inflationary gravity waves may be imprinted, allowing us to probe back to a fraction of a second after the big bang. In parallel with this, CMB experimenters are also planning new projects at other wavelengths, continuing the already established tradition (e.g. BLAST and SCUBA2) of using expertise and technology originally developed for mm-wave CMB observations to break new ground elsewhere.

Subject headings: Cosmic Microwave Background, Cosmology, Canada

1. INTRODUCTION

Measurements of the Cosmic Microwave Background radiation have provided a cornerstone to our understanding of cosmology, anchoring theories with precision measurements of the universe at z=1100, about 380,000 years after the Big Bang. The CMB alone provides tremendous resolving power for the cosmological parameters and it is rare to report any parameter measurement without using CMB data to constrain the fit. Canadian scientists and technology have been involved in nearly every important CMB result over the last decade and these measurements have established the standard cosmological model.

As the Canadian community enters into the process of its Long Range Plan, the WMAP collaboration, with involvement from CITA and UBC, has published its 7 year results (Jarosik *et al.* 2010, e.g.) and mapped the CMB temperature anisotropies to the cosmic variance limit out to $\ell \sim 550$. By many measures, the WMAP papers are the most cited scientific results in history. The Planck Satellite has been successfully launched and produced its First Light survey [6]. It is now in a mode of routine observations.

With definitive measurements of the temperature anisotropy out to moderate angular scales, the CMB community began refocusing its efforts about 5 years ago on fine angular scale anisotropies ($\ell > 2000$) and polarization. In both cases, more capable experiments have had to wait for technological breakthroughs–many with Canadians playing key roles. While early results have been reported, definitive measurements will require the better part of the next decade or longer.

1.1. *Fine Scale CMB Anisotropy*

At small angular scales there is a wealth of information about inflation and the growth of cosmic structure. The tilt of the primordial power spectrum is a key parameter encoding information about inflation. Beyond the exponentially damped tail, sources of secondary anisotropy dominate the power spectrum. The signature imprinted by inverse-Compton scattering of CMB photons with hot electrons in the intra-cluster medium, called the Sunyaev Zel'dovich (SZ) effect, provides a means of identifying distant galaxy clusters. The surface brightness of the SZ effect is insensitive to redshift and closely related to cluster mass, making it an ideal selection function for using the growth of structure through cluster counts to constrain cosmology. The small scale anisotropies are affected by weak lensing, providing a measure of the integrated matter along the line of sight which, amongst other things, can be used to weigh the neutrino species.

1.2. *CMB Polarization*

Experiments are only just beginning to have the sensitivity necessary to map the faint CMB polarization. The science is tantalizing. While the microwave background provides a data point 380,000 years after the big bang, gravity waves emitted from an early period of inflation carry information from a tiny fraction of a second after the big bang. If inflation occurred at a high enough energy scale, as the simplest models suggest, inflationary gravity waves will imprint a measurable large angular scale signature on the CMB polarization. One component of this signature, the "B-mode" polarization, provides a clean imprint on the microwave background. This is an experimental probe of the highest energy scales and earliest time in cosmic history.

At small angular scales, secondary scattering with matter along the line of sight provides a weak lensing signature that is measurable in the B-mode power spectra.

Much of the effort in the international CMB community today is focused around galaxy cluster surveys using fine angular scale CMB anisotropies and making definitive measurements of the CMB B-mode power spectrum.

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[6] http://www.esa.int/esaCP/SEM5CMFWNZF_index_0.html

2. CANADIAN ACHIEVEMENTS IN CMB RESEARCH OVER THE LAST DECADE

Canadian CMB research obtained international recognition with the pioneering measurement (Gush *et al.* 1990) of the frequency spectrum by the UBC team using COBRA, a sounding rocket experiment. Though results were just slightly behind the COBE satellite spectrum (Mather *et al.* 1990), the measurements were a factor of several more precise than COBE's initial results. The Gush group's style has been characteristic of the Canadian CMB community: relatively small university-based teams involved end-to-end with the experiment, from its initial design conception, its construction, commissioning, deployment, and data analysis. The lion's share of the work has been accomplished by graduate students and postdocs who receive "old-school" physics training spanning the full life of an experiment, something that has become quite rare today. The UBC group continued their program by building and flying BAM (Tucker *et al.* 1996) aboard a stratospheric balloon to measure the CMB anisotropy.

One of the most exciting results in cosmology to date has been the observation of the acoustic peaks in the CMB power spectrum by the Boomerang collaboration (de Bernardis *et al.* 2000; Netterfield *et al.* 2001), providing a measure of the curvature of space-time and demonstrating the universe to be flat within a couple percent, as inflation would suggest it should be. Netterfield was also involved with an earlier observation of CMB anisotropy (Netterfield *et al.* 1996) using the SK telescope operating from Saskatoon, Saskatchewan. The Toronto experimental cosmology group evolved from this heritage.

Not long after the acoustic peaks were observed, the Cosmic Background Imager (CBI) released its results on small angular scale anisotropy (Sievers *et al.* 2002), establishing the CITA group's expertise in the analysis of large CMB data sets and their cosmological interpretation.

The Wilkinson Microwave Anisotropy Probe (WMAP) satellite (Bennett *et al.* 2003) has revolutionized precision cosmology. Halpern has been involved with the experiment from the onset and key analyses have taken place at CITA. We note that the Canadian WMAP effort has proceeded without any funding from Canadian sources, other than individual NSERC discovery grants.

A recent breakthrough for CMB research was the development of technology that allows the construction of radiometers with thousands of pixels operating near the photon noise limit. The increased sensitivity allows for precise measurements on small angular scales and for observation of the faint polarization signature. The Sunyaev-Zel'dovich Effect (SZe) maps of the Bullet cluster (Halverson *et al.* 2009) using the APEX-SZ camera (Dobbs *et al.* 2006) were the first scientific results obtained with a large (300 element) multiplexed array of bolometers. The same technology was used by the South Pole Telescope (Carlstrom *et al.* 2009) for the first discovery of previously unknown clusters using the SZe (Staniszewski *et al.* 2009). The third and newest node of experimental cosmology in Canada, the McGill group, evolved from Dobbs' contribution developing the multiplexed readout system for these experiments. The Atacama Cosmology Telescope (ACT) (Fowler *et al.* 2007) currently has the largest number of bolometers from a single experiment on the sky and has also announced discoveries of new galaxy clusters using the SZe. A photo of the ACT telescope, under construction in Port Coquitllam, B.C. is shown in Fig. 1. ACT and APEX-SZ are located at 5000 m on the Atacama Plateau in Chile, very near to the ALMA site. Canadians play lead roles in the end-to-end realization of all three of these experiments (APEX-SZ, SPT, and ACT): early design, key technology, data analysis, and cosmological interpretation.

FIG. 1.— The Atacama Cosmology Telescope (ACT) under construction in Port Coquitllam, B.C. April, 2006. ACT has been recording measurements of small angular scale CMB anisotropies for two years and represents the largest number of TES detectors on the sky in a single experiment. The readout system warm electronics were built at UBC.

The Planck Satellite was launched May 14, 2009 and began routine observations from its L2 orbit in July. Planck has finer angular resolution, more bands extending to higher frequency, higher sensitivity, and better polarization capabilities than WMAP. It has a good shot at an early detection of B-mode polarization from inflationary gravity waves and will be a focus for Canadian CMB data analysis over the next decade. The Canadian effort is supported by Canadian Space Agency (CSA). Dick Bond leads the Canadian team for the High Frequency Instrument (HFI) and Douglas Scott leads the Canadian team for the Low Frequency Instrument (LFI).

EBEX (Granger *et al.* 2008) and SPIDER (Crill *et al.* 2008) are two new CMB polarization experiments that will be flown aboard NASA stratospheric balloons. The McGill group is heavily involved with EBEX (Figure 2), while Toronto and UBC play leading roles with SPIDER. Both experiments rely heavily on Canadian technology including the attitude control systems and the multiplexed readout systems. Two technological milestones were reached in June 2009 with the test flight of EBEX. This marked the first demonstration in a space-like environment of (1) a large array of Transition Edge Sensor (TES) bolometers and (2) a SQUID-based multiplexed readout system. These are enabling technologies for a future CMB polarization satellite, which is the long term goal for much of international community.

In addition to the CMB experiments described above, Canadian CMB researchers have used their expertise

FIG. 2.— The EBEX balloon-borne polarimeter was launched by NASA for a test flight in June 2009, marking the first operation of a large array of transition edge sensor bolometers and a multiplexed SQUID readout system in a space-like environment. The experiment is scheduled for its science flight in 2011. The readout system was designed and built at McGill university.

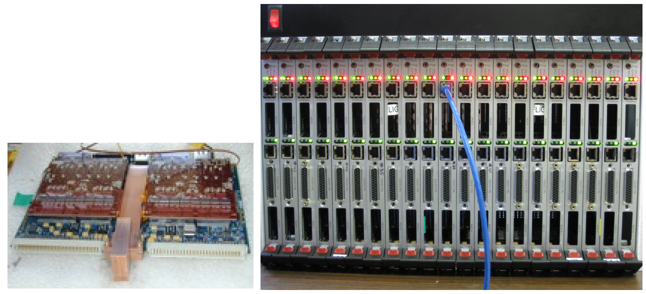

FIG. 3.— The McGill digital frequency domain multiplexer (one FPGA circuit board shown left, and a full crate of electronics providing readout for 1000 channels shown right) is being deployed on EBEX, POLARBEAR, ASTE continuum camera, and the South Pole Telescope polarimeter. It was test flown in June 2009 on the EBEX balloon polarimeter marking the first demonstration in a space-like environment of (1) a large array of Transition Edge Sensor (TES) bolometers and (2) a SQUID-based multiplexed readout system. These are enabling technologies for a future CMB polarization satellite, which is the long term goal for much of international community.

with CMB-related technology and experience with low signal to noise sky signals to enable experiments at other wavelengths. These include the SCUBA2 project, which uses the UBC readout electronics and the BLAST sub-mm balloon borne telescope (Pascale *et al.* 2009), which recently released striking maps of the sub-mm universe (e.g. (Devlin *et al.* 2009)). These are just a few of many examples.

3. UNIQUE CANADIAN CAPABILITIES

The Canadian CMB research community has developed many unique capabilities for which it has a role of international leadership. These include the following.

Multiplexed Readout Electronics for Bolometers:

Presently the vast majority of CMB experiments have chosen Transition Edge Sensor (TES) bolometers for detection of mm-wave light, consistent with expectations from the U.S. Task Force for Cosmic Microwave Background Research (Weiss *et al.* 2005), that recommended "technology development leading to receivers that contain a thousand or more polarization sensitive detectors, and adequate support for the facilities that produce these detectors." The recommendation also identified that "It is important to keep open a variety of approaches until a clear technological winner has emerged. Nevertheless, highest priority needs to be given to the development of bolometer-based polarization sensitive receivers." TES detectors allow for lithographic construction of kilo-pixel arrays that approach the photon statistics limit. For arrays of a thousand or more TES detectors, constraints on complexity and heat load make it necessary to multiplex the signal from many bolometers at the cold stage into a smaller number of output channels–multiplexed readout is key technology in enabling large TES arrays.

Almost all TES bolometers that are presently observing the sky or scheduled to deploy in the upcoming decade are read out using multiplexed technology co-developed by Canadian institutions. The UBC group, in partnership with NIST who provides the superconducting cold components, has developed the room temperature electronics for the time domain multiplexed system (TDM) (Battistelli *et al.* 2008) (figure 4). The TDM is in use (or scheduled for use) on ACT, ABS, Bicep2, Clover, Keck, Poincare, Piper, Poincare, Spider, all funded CMB experiments. In addition, TDM is being used for other wavelengths, including the SCUBA2, Z-specII, and Goddard Sofia cameras. The McGill group has developed a digital frequency domain multiplexer (DfMUX) (Dobbs *et al.* 2008) (figure 3) which builds on the heritage of the analog frequency domain multiplexer that Dobbs co-developed while at Berkeley. The DfMUX system uses NIST SQUIDs for cold pre-amplification. The frequency domain system is in use or scheduled for deployment on APEX-SZ and South Pole Telescope (analog version) and EBEX, POLARBEAR, South Pole Telescope Polarimeter, and ASTE (digital version).

Canadians have established international leadership in technology for TES detector multiplexing, which will likely earn us an invitation to participate in a future CMB polarization satellite.

Electronics for Pointing and Control of Balloon Payloads:

The Toronto instrumentation team, led by Netterfield, have established themselves as world leaders in systems for control of pointed balloon payloads. They are presently operating out of a high-bay facility purpose-built for developing balloon payloads. Their attitude control system (ACS) was originally developed for BLAST. It will be used for BLASTpol and SPIDER and forms the foundation of the EBEX mission ACS. This is a well designed, modular system that will undoubtedly be adopted by other missions as well.

Online Monitoring Software:

KST is an online monitoring software system, originally conceived in Netterfield's group and now being developed and maintained by both the UBC and Toronto/CITA groups. It allows scientists to accurately monitor timestreams and derived data products from timestreams in realtime.

The KST effort receives funding from the CSA through its Planck programs and is used by the international Planck collaboration for trend analysis and instrument monitoring. Beyond Planck, it is used by just about every CMB research group on the planet.

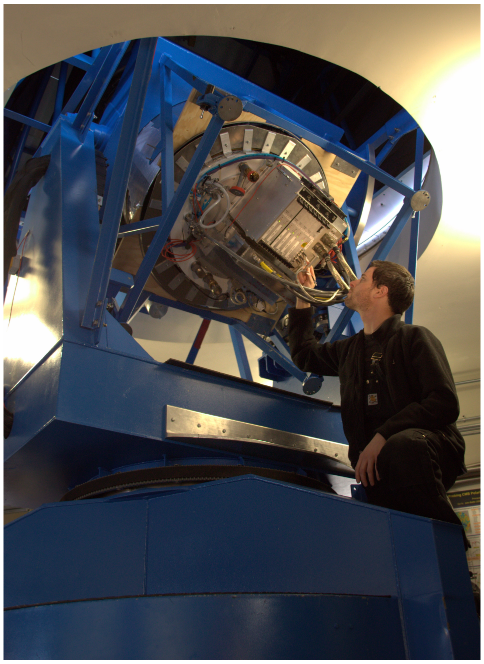

Fig. 4.— The UBC Multi Channel Electronics are shown on the BICEP2 experiment at the South Pole in Feb 2010. This system will be flown on the SPIDER balloon borne polarimeter in 2011 and is deployed or being deployed on the ACT, ABS, Bicep2, Clover, Keck, Poincare, Piper, Poincare, Spider, SCUBA2, Z-specII, and Goddard Sofia instruments.

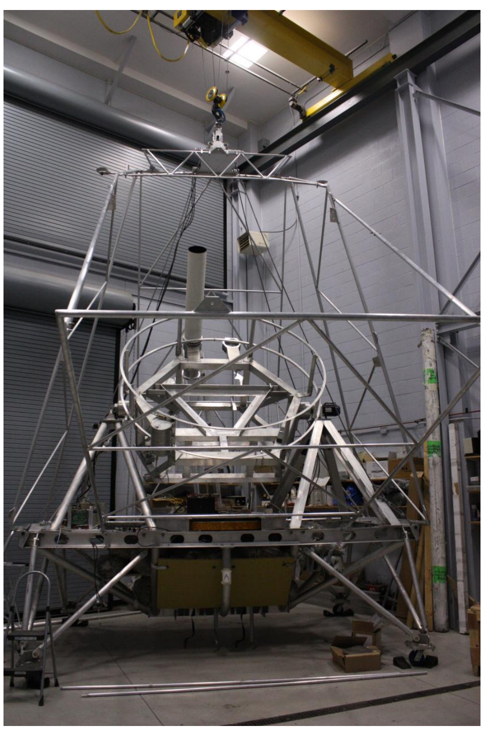

Fig. 5.— The BLASTpol gondola is shown in the University of Toronto high-bay, a facility constructed specifically for the development of balloon payloads. The BLAST attitude control system is being used for BLAST, EBEX, BLASTpol, and SPIDER. It will likely be used for others as well.

Analysis Software and Algorithms:

Canadian researchers have been key players for the analysis of CMB data and its cosmological interpretation. This leadership role has been exercised for both experiments that have Canadian hardware contributions and those that do not, such as CBI, ACBAR, and Planck.

The computing resources at CITA have helped to enable this role.

Foregrounds: The HIA-DRAO has aided CMB research by carrying out the Planck Deep Field Survey to measure foreground emission and by offering a suitable dish and an excellent northern site for a 10 GHz all sky mapping proposal. DRAO's mandate for supporting University initiatives is crucial to these efforts.

4. HIGHLY QUALIFIED PERSONNEL

The experimental CMB field provides second-to-none training opportunities for students and postdocs. The timeframe of a typical CMB experiment provides a unique opportunity and skill-set to students and postdocs. Within the span of a typical PhD they have the opportunity to participate in the end-to-end development, commissioning, and analysis of a cutting edge scientific instrument. This training environment is one of the most important contributions of the lab to Canadian academia and industry.

The groups involved with instrumentation (Dobbs, Halpern, Netterfield) are presently providing training and field experience to five postdocs, six professional staff (primarily young engineers), eleven graduate students, and a half dozen undergraduates. We stress the uniqueness of the training these individuals receive and emphasize the importance of their future contributions to the Canadian academic, industrial, and even military scenes. In addition there are several postdocs, research associates, graduates students and undergrads working on data analysis projects with the theory-background members of the community (Bond, Holder, Scott).

5. CANADIAN OPPORTUNITIES

In the first half of the upcoming decade, the CMB community will be focusing on deployment, operation, and analysis of the new generation of instruments it has copioneered with its international partners. These include (with senior researcher having primary involvement in parentheses):

- The South Pole Telescope and its polarimeter upgrade (Dobbs and Holder)
  SPT will continue its small angular scale temperature anisotropy survey until roughly 2012, when it will be upgraded with a polarization sensitive camera using McGill readout electronics.

- The Atacama Cosmology Telescope (Bond and Halpern)
  ACT is releasing its first science results now and plans to upgrade its camera for polarization sensitivity within a couple years.

- KECK Telescope (Halpern)
  The BICEP telescope at the South Pole has evolved into a much more ambitious large angular scale polarimeter called Keck. UBC has provided the warm readout electronics.

- POLARBEAR (Dobbs)
  Polarbear is a ground-based experiment being sited on the Chilean Atacama plateau. McGill provides the readout.

- EBEX (Dobbs)
  The EBEX balloon-borne polarimeter had its test flight in June 2009 and is scheduled for a science flight in 2011.

- SPIDER (Bond, Halpern, Netterfield)
  SPIDER, which uses the UBC readout electronics and Toronto ACS, will be test flown in 2010/11 and is scheduled for a science flight a year later.

- Plank LFI and HFI (Bond and Scott)
  While the Planck mission duration is just 2 years, data analysis will continue for several years afterwards.

we have listed only those projects that have end-to-end Canadian involvement and have not included experiments to which Canadians are providing technology but have chosen not to have a comprehensive role in.

Beyond mm-wavelengths, the Toronto group is presently heavily involved with building a polarization sensitive sub-mm balloon-borne instrument, BLASTpol, and the UBC group has built the readout electronics for SCUBA2 and is commissioning the instrument.

Looking forward to new experiments, the community is primarily eyeing CMB polarization science for the latter half of the upcoming decade:

- The international CMB community has converged towards the goal of a dedicated CMB polarization satellite, commonly referred to as CMBpol in the U.S.A. The European effort has gone by the name BPOL. The Japanese community is studying a small-sat polarimeter called LITEBIRD. ASP is a midex proposal for a polarizing FT spectrometer acting as a low ℓ polarization probe. Whichever effort gains traction, Canadians will likely be involved with readout electronics, software, and data analysis. It is feasible to consider a mid-sized Canadian led mission as well–Canada has the necessary expertise.

- A follow-up to CSA supported balloon missions EBEX and Spider. This mission would combine the best of these two pathfinder missions and be a pre-cursor to a large international satellite mission, described above.

At the same time, the community is continuing its tradition of leveraging its experience within the CMB field to increase research opportunities in other related fields of astronomy. This has been the case for sub-mm astronomy with BLAST and SCUBA2. Looking forward:

- Netterfield is studying new opportunities to apply his group's ballooning expertise to a balloon-born wide field optical imager instrument.

- Bond, Dobbs and Halpern have been studying and designing a pan-Canadian 21 cm hydrogen intensity mapping experiment called CHIME that will use Baryon Acoustic Oscillations (BAO) to follow the CMB's acoustic peaks down to the lower redshifts (z=1-3) where dark energy 'turns on'. The experiment would be hosted at the DRAO in Penticton and constructed of digital fast Fourier transform telescopes. The cost and timeframe will be of the same scale as the ground-based CMB experiments discussed here. Refer to the 21 cm whitepaper for more info.

6. CHALLENGES FOR CMB RESEARCH IN CANADA

Despite the achievements of the community to date, there remains significant challenges for this research in Canada.

The CMB community has achieved internationally acclaimed results and developed world leading technology, sometimes with little or no Canadian funding. Though Canadians have been at the forefront of some of the most important measurements of the CMB (often as first authors in large international projects), PI-level leadership of these projects has justifiably remained in the country providing the lion's share of funding - this has not recently been in Canada. The community aspires for a Canadian led project in the upcoming decade to allow Canadian researchers to fulfill their potential. In part because the CMB community is small in comparison to the larger Canadian astronomy community, funding for such a project may be difficult. This is particularly true for ground-based opportunities where the CSA is not involved.

It is noted that many of today's most prominent CMB experiments with Canadian partnership (e.g. WMAP, ACT, SPT, POLARBEAR, Ebex, and Spider) have gone forward without a presence in the previous LRP, and indeed the majority of these were not yet on the horizon. The timescale for these experiments is often faster than the LRP lifecyle. This means that one of the most important challenges for the CMB community is being able to respond to opportunities and realize new ideas on a short time scale. The community has demonstrated it can do this in the format of international partnerships. It is important that funding vehicles exist that will allow Canadians to realize their potential, both in partnerships (as has been the case) and Canadian-led enterprises. CFI and CSA are likely to be important in this regard.

The importance of the Canadian Space Agency (CSA) for CMB research across Canada cannot be overstated. It funds balloon missions such as EBEX and SPIDER and the Planck satellite. It is anticipated that the expertise developed in Canada will continue to make Canadians welcome partners for a future CMB polarization satellite, presumably for the development of the detector readout system and software/analysis, which needs continued support from CSA. It is equally important that CSA fund the science return for its space astronomy missions at an adequate level. CSA should endeavor to fund science analyses through the lifetime of the mission, probably using an SSEP (grant not contract) vehicle, so long as these missions continue to hold promise for excellent scientific results and excellent scientists are signed on to the projects.

The CSA's move towards expanded infrastructure and funding support for small missions (such as balloon payloads and nano-sats) is welcome to the CMB field and extremely important for capacity building in space technology.

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