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# SATELLITE MISSION OPPORTUNITIES FOR CMB POLARIZATION: WHITE PAPER FOR THE CANADIAN LRP MIDTERM REVIEW

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## ABSTRACT

The cosmic microwave background (CMB) is a cornerstone for precision cosmology and Canadian experimenters have been involved with the majority of significant results over the last 25 years. Canada's footprint has grown substantially since the LRP, with 4 out of 10 co-authors of this paper having been hired since 2010.

The next frontier is a detailed characterization of CMB polarization, with a focus on the subtle B-mode signature. Perhaps the most exciting prospect is the ability to look beyond the surface of last scattering to see or place stringent limits on gravity waves emitted from a period of inflation a fraction of a second after the Big Bang. Canadians have played key instrumentation, analysis, and interpretation roles in all B-mode results that have been reported to date.

Presently, the vast majority of ground- and balloon-based CMB experiments use TES bolometers, and all of these experiments read out their detector arrays with Canadian technology. TES bolometers are the leading technology for future satellites as well.

A dedicated CMB polarization satellite will be a large international partnership. With support from the Canadian Space Agency, Canadian researchers are uniquely positioned to play an international leadership role in this mission, partnering with one or more other agencies to make the definitive measurement of large to medium angular scale CMB polarization. This white paper is written to seek community endorsement for a high prioritization of a Canadian partnership contribution to a near-term future CMB polarization satellite.

## 1. SCIENTIFIC BACKGROUND

In the last few decades, the cosmic microwave background (CMB) has been a tremendous success story. Our understanding of the universe has been dramatically sharpened by a sequence of datasets with increasing statistical power.

So far, almost all of the statistical power of the CMB has come from precision measurements of the unpolarized (or temperature) signal. The next 5–10 years will be a turning point in the field: instruments will be sufficiently sensitive to make equally precise measurements of CMB *polarization*, unlocking new cosmological information and qualitatively new science.

High signal-to-noise maps of CMB E-mode polarization will permit reconstruction of the reionization history of our universe, and will also probe interactions between the dark matter sector and Standard Model particles. Measurements of B-mode polarization will allow us to search for cosmological gravity waves with a sensitivity several orders of magnitude better than current limits, thus probing the physics of inflation to unprecedented precision. Gravitational lensing also generates a guaranteed B-mode signal which is extremely sensitive to the physics of dark energy and the neutrino sector. Future CMB observations can also constrain the neutrino sector in a different way, by measuring inverse Compton scattering of CMB photons from hot gas in the IGM (the Sunyaev-Zeldovich effect). It should soon be possible to measure neutrino masses with statistical errors which are a few times better than the minimum mass (58 meV) allowed by neutrino oscillation experiments, a major milestone for cosmology.

Taken together, these new observational windows on fundamental physics will provide important clues on the road toward solving some of the deepest problems in modern physics: the nature of dark matter, dark energy, and the physics responsible for generating the initial fluctuations.

## 2. MID-TERM REVIEW CONTEXT

The first half of the 2010–2020 Canadian Astronomy Long Range Plan has seen remarkable progress in Cosmic Microwave Background (CMB) observations. The WMAP collaboration has released its final results (Hinshaw et al. 2013) and Planck results on temperature anisotropy, CMB lensing, and galaxy clusters are released. Planck polarization results are expected this year. The South Pole Telescope and Atacama Cosmology Telescope have provided the state of the art for fine-scale CMB observations, detailing the temperature anisotropy damping tail and unveiling a new census of matter in the Universe with Sunyaev Zeldovich galaxy cluster surveys. Measurements of CMB polarization have come of age with first detections of gravitational lensing induced B-modes from POLARBEAR (POLARBEAR 2014) and SPT-Pol (Hanson *et al.* 2013) and the hunt for the signature of inflationary gravity waves at the forefront in the ex-

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pert and public eye since the BICEP2 (BICEP2 2014) results were released in March 2014.

Moving forward, the next decade will see increased focus on CMB polarization results, emphasizing primordial B-modes at large angular scale and secondary effects at small angular scale that will allow for accurate measurements of the neutrino sector ($N_{\rm eff}$ the number of effective neutrino species and $\sum M_\nu$ the sum of the neutrino masses) and a census of mass along the line of sight.

In terms of instruments for the future, the international community is becoming focused on two strategies. This is in stark contrast to the recent past, where a relatively large number of low-cost experiments competed for early results. The strategies are: (1) A "stage-4" ground based observatory, jointly funded by the NSF and DOE in the US that is likely to merge several collaboration in the community and consist of an array of telescopes configured to observe in concert. With this telescope array, "stage-4" would have the order of 100,000 detectors, stretching across many atmospheric windows, to observe with exquisite sensitivity and fast mapping speed. Canadians will certainly be involved with this effort, though it is outside the scope of the present mid-term review. (2) For large angular scale polarization across a much larger range of frequencies, an orbital mission is needed – the focus of this whitepaper.

### 2.1. *Canadian Achievements in CMB Science*

Canadians have played key roles in nearly every important CMB result to appear in the past 25 years. The vast majority of contemporary CMB data flows through Canadian hardware or software technology today, on ground-based, sub-orbital, and orbital platforms.

Here is a sample of past CMB results in which Canadians have played key roles:

- Measurement of the CMB frequency spectrum with the COBRA sounding rocket (Gush *et al.* 1990). This small team of several researchers produced a determination of the CMB temperature that was more precise than the initial measurements from the COBE (Mather *et al.* 1990) collaboration (COBE results were, however, released prior to the COBRA measurement).

- Observation of acoustic peaks in the CMB power spectrum by the Boomerang collaboration (de Bernardis *et al.* 2000),(Netterfield *et al.* 2001). This measurement demonstrated that the universe is flat to within a couple percent, as inflation suggests it should be.

- Sunyaev Zeldovich (SZ) Effect: the first discovery of previously-unknown clusters using the SZe was achieved with the South Pole Telescope (Staniszewski *et al.* 2009). Today, state of the art SZ galaxy cluster surveys come from ACT (Hasselfield *et al.* 2013), Planck (Planck XXIX 2013) and SPT (Bleem *et al.* 2014). The *kinetic* Sunyaev Zeldovich effect has also been observed by ACT in correlation with galaxy pairs in the Sloan Digital Sky Survey (Hand *et al.* 2012). This allows inference of cluster masses from the gravitational acceleration they produce.

- Definitive measurements of the CMB temperature power spectrum today come from Planck (Planck XV 2013) and WMAP (Bennett *et al.* 2013) at larger angular scales, and SPT and ACT (Das *et al.* 2014) at smaller angular scales.

- First observation of small-scale B-mode polarization from gravitational lensing. A $> 7\sigma$ detection was made by SPTPol (Hanson *et al.* 2013) by cross-correlating a B-mode template with the measured B-mode polarization spectrum from SPTPol. The B-mode template was produced from a combination of a Herschel-SPIRE map and the SPT E-mode polarization map. The B-mode polarization in auto-correlation was observed by POLARBEAR (POLARBEAR 2014) at small angular scales (where gravitational lensing dominates), rejecting the no-lensing hypothesis at 97.2% confidence. The temperature and polarization power spectra have also been combined with measurements of gravitational lensing in CMB intensity to provide evidence for dark energy using the CMB alone (Sherwin *et al.* 2011).

- Observation of excess power in the 150 GHz B-mode power spectrum at large angular scales with BICEP2 (BICEP2 2014). The BICEP2 team has interpreted these measurements as the signature of inflationary gravity waves, though other teams (e.g. (Planck XXX 2014)) have argued that the signal is plausibly caused by dust in our own Galaxy. More measurements are needed to reach consensus.

- Planck all-sky polarization – new results are expected this year from the Planck mission. Several key analyses are led by Canadians, Canadian software is used for online monitoring, and Canadians play key senior roles in the mission.

## 3. UNIQUE CANADIAN CAPABILITIES

### 3.1. *Expertise and Know-how*

Canadians have played key roles in nearly every major CMB result over the last 25 years. In many cases, Canadians have provided hardware, theoretical algorithms, know-how, or expertise that is available nowhere else in the world. It is clear that the most important contribution that Canada can make to a CMB polarization mission is its people – faculty members and financial support for postdocs and graduate students to work along side them. The CMB community has grown substantially in Canada since the LRP 2010 was released. This white paper is co-authored by Canadian faculty members who have co-authored major experimental results. It is notable that 4 of the 10 co-authors were newly hired since the LRP2010, and that these hires span assistant, associate, and full professor faculty levels.

In addition to hardware and experimental results, Canadian theorists have been involved in developing many of the tools that are now used routinely for analysis and interpretation of data from all CMB experiments. This has led to Canadians being invited to contribute substantial effort on the analysis side for many experiments (Planck being a prime example).

### 3.2. *Detector Readout Electronics*

Essentially all TES bolometers that are presently observing the CMB 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). The TDM is used for the Atacama Cosmology telescope, Bicep2, Keck, Piper, CLASS, and Spider CMB experiments. In addition, TDM is being used for other wavelengths, including the SCUBA2, ZEUS-2, and Goddard SOFIA cameras. The McGill group has developed the digital frequency domain multiplexer (DfMUX) (Dobbs *et al.* 2008) electronics. The DfMUX system uses cold components developed at Berkeley and NIST SQUIDs for cold preamplification. The frequency domain system is used for APEX-SZ, ASTE-continuum camera, South Pole Telescope, EBEX, POLARBEAR, and the Simon's Array.

Canadian technologies are the only TES readout systems that has been operated in a space-like environment. The successful EBEX stratospheric balloon flights in 2009 and 2012 demonstrate that DfMUX is at Technical Readiness Level 5 and the TDM system is schedule to fly on the SPIDER stratospheric balloon during the 2014/15 austral season.

The CSA has recognized Canadian leadership in detector and readout systems for millimetre to far-IR (several years ago when CSA made its list of a dozen or so "signature Canadian Technologies for space", TES readout systems appeared along with the CanadaARM and other technologies). Recently, the CSA funded the development and construction of flight-representative models of key elements of the DfMUX readout system through its Space Technology Development Program contracts. This partnership between McGill and COM DEV demonstrated the power consumption, radiation hardness, environmental specifications, and system layout necessary for a satellite mission. Based on this work, the Canadian DfMUX readout was made the baseline for the Japan Aerospace Exploration Agency (JAXA) LiteBIRD CMB polarization mission, discussed below.

Several Canadian industrial partners have played key roles in these readout systems and are well positioned to play roles for satellite readout systems.

### 3.3. *Online Monitoring and Analysis Software/Algorithms*

Canada provides online monitoring software, built on the universal KST (https://kst-plot.kde.org) realtime monitoring software, for the Planck Mission. KST allows scientists to accurately monitor timestreams and derived data products from timestreams in realtime. The Planck collaboration uses it for trend analysis and instrument monitoring. Beyond Planck, it is used by just about every CMB research group internationally.

## 4. MISSION OPPORTUNITIES

### 4.1. *Partnership with JAXA: LiteBIRD*

LiteBIRD (Matsumura *et al.* 2014) is a JAXA-led satellite mission designed to measure the polarization of the cosmic microwave background (CMB) radiation. The LiteBIRD working group consists of more than 70 members from Japan, USA, Canada and Germany. The working group is preparing a mission definition review in 2014–2015 and a system requirement review in 2015–2016.

The Institute of Space and Astronautical Science (ISAS) at JAXA formulated an agressive roadmap for space science and exploration in 2013. Three strategic JAXA-led flagship science missions are planned within the next ten years, with launch dates in 2015, 2021 and 2025. The mission cost envelope is \$300M, including the satellite bus, instrument, launch, and operations. Astro-H is assigned the 2015 slot, with LiteBIRD and WISH being the highest ranked contenders for the other slots – the LiteBIRD team's goal is to be ready for the launch slot in 2021.

More broadly beyond JAXA, the project has received a snowballing of support from the scientific community and funding agencies in Japan. LiteBIRD was one of 5 projects across all science initiatives that received Japans Ministry of Education, Culture, Sports, Science and Technology's top ranking for science impact and timeliness. It is ranked among the highest priority large-scale projects by the Science Council of Japan (SCJ).

LiteBIRD employs a kilo-pixel superconducting detector array on a cryogenically cooled sub-Kelvin focal plane, with an optical system at a temperature of 4 K. It will have an angular resolution of 30 arcminutes at 150 GHz (covering multipoles $2 < \ell < 300$) and total sensitivity of $\sim 2\mu$K·arcminute. The baseline design uses 2022 transition edge sensor (TES) bolometers divided into 304 low frequency (band centres at 60, 78, 100 GHz) and 370 high frequency (band centres at 140, 195 and 280 GHz) trichroic pixels. The precise distribution of bands may evolve as knowledge of foreground levels improves with the release of Planck data and deeper observations from the ground. The baseline design is for the detectors to be read out with the Canadian DfMux readout system.

The LiteBIRD working group and ISAS/JAXA have targeted key international collaborations. Specifically, LiteBIRD is pursuing partnerships with NASA for multichroic TES detector technology and a continuous 100 mK adiabatic demagnetization refrigerator, and with Canada for the DfMux readout.

### 4.2. *Partnership with ESA: PRISM or COrE+*

There is a strong community base of support for a new CMB polarization mission in Europe, building on the success of the Planck mission, which had substantial Canadian involvement. The community is now preparing a new proposal, called the Cosmic Origins Explorer (COrE+), for submission in January 2015 to fund a Phase A study for 2015–2018 and anticipated launch date of 2025. This is ESA's fourth opportunity within the current ESA Cosmic Vision program. The budgetary envelope of the M4 mission is expected not to exceed about 450M €, which typically includes the launch vehicle, spacecraft and operations. The science instrument itself will be funded by participating nations and is estimated to cost an additional 200–300M €.

Since the COrE+ concept is presently being refined and is not yet public, for the purposes of this white paper, we will discuss PRISM (effectively its predecessor) as a representative ESA mission.

PRISM is described at http://www.prism-mission.org/, (astro-ph arXiv:1306.2259), which includes a white paper prepared in response to the European Space Agency call for white papers for the definition of the L2 and L3 missions in the ESA Science Program. It was proposed in May 2013 for the ESA Cosmic Visions program and is a proposed large-scale mission designed to measure the microwave to far-infrared sky in both intensity and polarization, as well as measuring the absolute frequency spectrum.

The polarimetric imager would feature a 3.5 m telescope cooled to 4 k, employing 30 broad and 300 narrow spectral bands, ranging from 30 to 6000 GHz. This will allow foreground subtraction and sensitivity for exquisite limits or detection of B-mode polarization from inflationary gravity waves, observations of the cosmic infrared background, and all-sky cluster surveys with much lower mass thresholds than Planck.

The spectrometer would include a reference blackbody and have much lower angular resolution, providing a measurement that is orders of magnitude better that FIRAS and provide a new window for constraining spectral distortions.

Natural contributions for Canada to this mission would be online monitoring and data reduction pipeline software development, the detector readout system, and/or a cryogenic blackbody system.

### 4.3. *Opportunities with NASA*

The U.S. community has been actively developing technology and mission concepts for CMB polarization. In particular, Americans lead the world in detector development for mm-wavelength observations with important R&D centers at Goddard, JPL, NIST, and UC Berkeley.

Presently, there is no US-led satellite mission in the proposal stage that we are aware of, and the present climate of fiscal constraint within NASA makes the near-term feasibility of a large NASA-led CMB mission uncertain.

However, US scientists are actively investigating future satellite missions, to be ready when the opportunity arises. NASA is likely to issue a Mid-class Explorer (MidEx) AO (cost cap $\sim$\$225M) in 2016 or 2017. Recent mission concepts have included EPIC, a large-scale mission led by JPL, and PIXIE (Kogut *et al.* 2014), a mid-scale mission that uses a novel combination of multi-moded optics and fourier transform spectroscopy. EPIC is based on Canadian-designed readout systems, and the PIXIE science team has several Canadian scientists in key roles.

Like PRISM, PIXIE has the capability to measure both the polarization anisotropy and spectral distortions. The PIXIE team is likely to propose for the next MidEx opportunity in 2016 or 2017. In the meantime, they are advancing the key technologies that PIXIE will require, including: 1) measuring the cross-polar performance of a multi-moded concentrator (Kogut *et al.* 2014); 2) characterizing the electro-thermal properties of the first-generation detectors; and 3) fabricating polarizing gratings for wavelengths $< 50$ $\mu$m.

It is very likely that a large-scale international mission will include a partnership with NASA, with their role focusing on the detector system. This is key for Canada, as Canadian readout technology has been deployed with American-built detector systems in many major facilities. Presently, there is a US Mission of Opportunity proposal being prepared for partnership in LiteBIRD. A JAXA (telescope/payload), NASA (detector focal plane), and CSA (readout electronics) partnership is an example of the sort of near-term future opportunity that should be considered for the Canadian mid-term review of the Long Range Plan. US researchers are also likely to play an important role with the detector systems of an ESA mission.

## 5. SUMMARY

The next decade of CMB instrument development will focus on a new generation "stage-4" ground-based experiment and a CMB polarization satellite. Canadians are likely to play a key role in both.

For the CMB polarization satellite, long term planning is needed with endorsement from the Canadian astronomical community in order for the Space Agency to move forward exploring possible partnerships with ESA, JAXA and/or NASA. This white paper asks for the community's endorsement to explore these possibilities, with the goal that Canada, through the Canadian Space Agency, explore a partnership role in one of these missions. This request may be summarized:

*Canadian Partnership Investment in Mid-sized Space Mission for CMB-polarization*

*The signature of gravity waves from inflation in the CMB B-mode polarization offers the possibility of observing the universe a fraction of a second after the Big Bang. It provides a window on energy scales near $10^{16}$ GeV, 13 orders of magnitude above what is is accessible to earth-based colliders. The response to the BICEP2 announcement highlights both the scientific importance of, and popular interest in, observational constraints on the beginning of our universe. More precise measurements of CMB B-modes also offer new constraints on the neutrino sector and provide a better census of matter in the Universe.*

*Canadians have played key roles in the vast majority of significant CMB results over the last 25 years. Essentially all TES bolometers that are presently observing the CMB or soon to be deployed are read out using multiplexed technology co-developed by Canadian institutions. Many of the highest impact CMB experiments rely on Canadian researchers playing key roles in the data analysis. Canadians, with their established expertise and know-how, coupled with unique hardware and software technologies, are sought-after partners for CMB polarization missions that are now in the planning stages. Canadas role, supported by the Canadian Space Agency, should include involvement in the Phase A studies for these missions and – if the science potential and technology achievements justify it – a partnership that may include hardware, software, and/or data analysis. Providing flight hardware for a partnership mission is likely to cost \$10–30M and would involve direct collaboration between Canadian industry and universities*

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