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COSMIC BACKGROUND RADIATION THEORY AND ANALYSIS: WHITEPAPER FOR THE CANADIAN LONG RANGE PLAN IN ASTRONOMY

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ABSTRACT

Canada has played a seminal role in the development of all aspects of the theory and analysis of the cosmic microwave background radiation (CMB), a very wide topic connecting the exotic particle physics of the early and late universe to the gastrophysical development of the cosmic web and to the detailed properties of extragalactic sources and Galactic foregrounds. CMB studies are in a golden age, with current and future high precision experiments allowing accurate determination of a myriad of cosmological parameters describing the content, structure and evolution of the Universe. In Canada, there is a very close collaboration of theorists and experimentalists, and superb international ties to major groups in the US and Europe, including the all-sky WMAP and Planck satellite consortia, and ground and balloon-based polarization and high resolution teams. To sustain this effort, continued access to high performance computing for end-to-end CMB analysis and for extensive large scale hydrodynamical cosmic simulations is essential. The ability to hire groups of CMB postdoctoral fellows in multiple centres across Canada beyond the minimal level that is possible with NSERC Discovery Grants is necessary for us to be effective in and for international CMB projects.

Subject headings:

1. OVERVIEW OF CMB THEORETICAL ISSUES

Canada has played a large role in the development of all aspects of the theory of the cosmic microwave background radiation (CMB). The theoretical issues needed to be addressed for the complete treatment of CMB physics include: (1) reaching into the fundamental physics of the early universe for initial conditions; (2) doing detailed but largely linear transport computations in the passage of the ionized primeval plasma to a mostly neutral one; (3) carrying the photon propagation through a late time universe when the the gas returns to a largely ionized state, touching upon almost all aspects of nonlinear astrophysical development of the cosmic web from the short-distance "first stars" regime through galaxy cluster formation — including in particular Compton scattering by hot gas (the thermal and kinetic Sunyaev-Zeldovich effects); (4) and the CMB is fundamentally affected by the influence of dark energy and any residual homogeneous mean curvature energy on the evolution of the gravitational potential.

Each phase imprints upon the CMB signals parameter dependencies that allow their determination to remarkable precision. By any measure, the CMB success in determining (1) the mass-energy densities of baryons, dark matter, dark energy, and curvature, (2) the age of the Universe and Hubble expansion rate, and (3) the amplitude and structure of primordial perturbations, that has occurred over the decade immediately past has been an astounding accomplishment, with Canadians at the forefront; and there is much anticipation that, in the further pursuit of precision that this new decade is bringing, the error bars on the usual cosmological parameters will not just shrink, but subdominant phenomenon may well be unearthed. For example, we will be looking for: (1) isocurvature fluctuations in addition to the curvature ones that dominate, (2) imprints of defects such as cosmic strings, (2) the imprint of gravity waves on CMB polarization, (3) the degree to which scale invariance in the power spectrum is broken, (4) a (small) level of primordial non-Gaussianity, and other effects from the early universe; (5) small neutrino masses; (6) temporal structure in the reionization history of the gas; (7) how energy injection affects cluster gas over time; and so much more.

Many Canadians were involved in Science White Papers for the US National Academy of Sciences Astro2010 Decadal Survey, as is highlighted in the reference list for those for CMB-related science. All have a theory component to highlight what we want to learn and motivate proposed experimental programs.

2. OVERVIEW OF CMB ANALYSIS ISSUES

Connecting the theory to the analysis of an increasingly powerful set of CMB experiments has also had a long and successful history in Canada, dating from the pre-COBE-discovery era of the mid-eighties. Indeed the close collaboration of theorist and experimentalist that has become the modus operandi was pioneered by relations forged by Canadians in international collaborations. Canada continues to follow this pattern, playing major analysis roles in almost all of the new generation of high precision experiments: Boomerang, the Cosmic Background Imager, ACBAR, WMAP, and BLAST, with analysis ongoing; APEX, the Atacama Cosmology Telescope, the South Pole Telescope, the Planck satellite now; and BLASTpol, EBEX, Spider, ACTpol, SPTpol in the future.

Experimental aspects of the CMB in Canada have been well discussed in the LRP white paper. Indeed, the highly successful marriage of theory and experiment that the CMB represents means that some experimental topics are equally theoretical topics. The common ground is all aspects of the software for phenomenological analysis as one takes the data: (1) from raw time ordered data or interferometer visibilities; (2) through cleaning and deglitching; (3) through map-making and noise and systematics determination; (4) through separation of component signals, extragalactic sources, galactic foregrounds, as well as the CMB and Sunyaev-Zeldovich signals; (5) through 2D power spectrum determinations at all map stages, for polarization and total anisotropy; (6) explorations of non-Gaussian measures to describe complexities in the data which may have primordial causes as well as the dominant mundane ones from experimental systematics, sources and foregrounds.

3. CMB COMPUTATIONAL NEEDS

The computational requirements to do the theory and analysis in support of the experiments are very large indeed, and Canada must position itself to continue to play its leading role in this endeavour. The advent of the seven regional university consortia funded by CFI and provincial partners under the auspices of Compute Canada has been fundamental to the success we have had. A scenario in which the multi-disciplinary aspect of these consortia will not deliver enough cycles to astrophysics to satisfy our ever-growing needs is possible; or general high performance computing may not continue to be sufficiently supported at the federal and provincial levels to allow the necessary upgrades every few years to remain competitive. CMB theorists, in the generalized sense expressed in this White Paper, have a strong interest in ensuring the flow of astrophysical cycles for analysis and theory.

The theory of Gaussian primary anisotropies, those arising from linear physics operating in the early Universe, is in good shape. For the current data, speedy codes efficiently using past-history integrations such as CMBfast and CAMB are adequate, and have been "validated" with codes solving hierarchies of multipole equations. Such calculations, even with the large number of repetitions required for Markov Chain Monte Carlo statistical calculations of probability surfaces, are largely do-able with relatively modest computational facilities. As precision in the data improves, fresh looks at all aspects of the accuracy are being done. An example is work on the details of hydrogen and helium recombination with hundreds of atomic levels included, work in which Canada is playing a key role. The likelihood codes will become more sophisticated to reflect non-Gaussian complexities of component-separated data.

For the nonlinear regime, one wants to have not only a single large-scale computation of the highest resolution obtainable with a fixed set of cosmological parameters, but to allow the parameters and resolution to vary in the quest for the best set, with accurate error bars. Exploring how energy injection from stars, black holes, annihilating dark matter and other sources feeds back into the evolving gasdynamics requires the largest dynamic range feasible, and hence very large highly parallelized computer systems. This is compounded by the necessity to vary the inputs, including those defining the sub-grid star formation and energy injection prescriptions. Although Canadians have played and are playing a major role in the worldwide effort to develop increasingly powerful algorithms and efficient codes to implement them, there is a necessary-future demanded by the avalanche of CMB data that will require greater and greater computer capacity.

The analysis component reducing the time ordered data of thousands of detectors, as ACT and SPT have, and EBEX and Spider will have, to maps and other compressed forms is far beyond the already prodigious requirements of Planck data processing. Indeed, for ACT, the full-time usage of thousands of processors in Toronto has been needed.

4. CMB CONNECTIONS WITH THE THEORY AND ANALYSIS OF EXTRAGALACTIC SZ, SUB-MM AND RADIO SOURCES AND THE ISM

Major efforts by many groups around the world have been put into developing the statistical pipelines which process and clean the raw CMB data to allow efficient and accurate confrontation with the theory. The direct interface with observations of the many and ubiquitous non-Gaussian signals is much more complex than for Gaussian primary anisotropies. Because all the signals are superimposed, the separation of the primary, secondary, foreground and extragalactic components inevitably complicates the move from multifrequency CMB data to determination of cosmic parameters from "cleaned" primary CMB power spectra, even if these are the primary target to be extracted from the data. The sophistication level required for this statistical analysis aspect of CMB theory is high: processing timestreams or interferometer visibilities, making maps in position or "momentum" (multipole) space, filtering, cleaning, separating component signals, compressing, always with new tools to explore systematic effects and anomalies that inevitably appear. The step from raw data to primary total and E-mode and B-mode polarization power spectra is enormous, especially with full likelihood evaluations requiring a full theory of errors. Most of the developments had been driven by the compelling necessity of the CMB teams, consisting of theorists/analysts as well as experimentalists, to extract accurate science from beautiful large datasets such as Boomerang, CBI, ACT and SPT, yet remain within computational feasibility.

The largest grouping of theorists/analysts is in the Planck consortium, which draws Europeans, from essentially all ESA nations since ESA leads Planck, Americans, through NASA's large involvement, and Canadians through the CSA, with centres at UBC and the University of Toronto, but with wider-spread Canadian engagement.

We have already commented on how important studying the state of gas in the intra-cluster medium and beyond, in the extra-cluster cosmic web, is for CMB theory. Explorations showing a significant source of non-gravitational heating is needed to understand cluster observations have had a long history in Canada, and we continue to be at the forefront of efforts to understand the underlying physics. In spite of the uncertainties in inhomogeneous stochastic heating, there is hope that we can characterize the cluster gas states sufficiently well to determine broad-brush information such as the value of σ_8^2, the cluster-scale band-power of the density power spectrum, but we are not there yet. Major cross-fertilizations of observation and theory will be needed if clusters will be useful for the higher precision required for dark energy studies, and that will be very actively pursued in

Canada, necessarily so because of our significant involvement in ACT and SPT and X-ray studies.

The study of the far infrared and submillimetre background associated with dusty galaxies, with its Poissonian and continuous clustering components, is arguably a CMB science, and has utilized over the years many CMB tools, including ones developed in Canada: theory for SCUBA, BLAST and Hershel are therefore intimately connected to CMB work. the extragalactic radio source background is also a fundamental subject of concern to the generalized CMB theorist. The desire is not just to rid the sky of such contaminants of the pristine primary CMB signal, but to study the cosmological aspects of these residuals. The concentration of such sources in regions that will give significant SZ signals means that decontamination is needed.

For all source types, the higher resolution afforded by, for example, the Green Bank Telescope, ALMA, the EVLA, CARMA and other interferometers, is essential follow-up, and will lead CMB theorists into such astronomical realms, indeed already has for some.

The statistically inhomogeneous and highly non-Gaussian Galactic foregrounds are perhaps more of a subject for an interstellar medium white paper, but characterizing their total intensity and polarization is necessary to CMB as we dig further and further to higher precision, in quest of, for example, the very tiny polarization signal induced by gravity waves (the "B-mode"). Canadian expertise will ideally blend in the twin goals of cosmology and ISM. This is already occurring in the Canadian Planck community.

5. CMB CONNECTIONS TO EARLY UNIVERSE PHYSICS

There is a large world-wide community of early universe physicists who are very excited about the CMB results, and will often now take their theories far enough to be able to make specific predictions for the theory's impact on the CMB. Canada is a hot-bed of such activity, with active researchers in Quebec, Ontario, Alberta and BC. It is one of the few areas that can lead to tests of string theory. Modifications of gravity theory may be detectable with Planck, and if not, will be significantly constrained. There is of course intense interest in CERN's Large Hadronic Collider in the physics community, and the interplay with cosmological information will be very exciting over the next decade. And there is nothing like a bona fide CMB anomaly — whether power spectrum asymmetries, downturns or glitches, non-Gaussian cold spots, strangely correlated multipoles — to fire theoretical imaginations of exotic early and later universe happenings, even if the ultimate solutions will turn out to be the more mundane systematic or foreground related.

All inflation models predict there will be gravity wave quantum noise, generating tensor perturbation components to the total and polarization anisotropies, in particular to the B-mode at multipoles below 100, but differ wildly in the amount, and in particular whether they will be detectable. The tensor-to-scalar power ratio r is just proportional to the acceleration parameter during inflation. In most, but not all, models of the eighties and nineties, r was predicted to be between about 0.03 and 0.5; in string-theory-motivated inflation models and in cyclic models, very small, undetectable, r's are the typical values, although alternatives with measurable values are possible. EBEX, Spider and Planck are three experiments with strong Canadian participation that could make a B-mode detection at $\pm.02$ that would profoundly affect the allowed set of early universe theories, of inflation or otherwise. Even a strong upper limit would be very valuable. The case for a CMBpol to go for accurate B-mode power spectrum determination near the cosmic variance limit and a tenth of a percent precision in r, which would be a major international space initiative, will depend upon what these three experiments, and others, find. If CMBpol happens, Canada should be involved, as the LRP White Paper on CMB Experiments also notes.

All inflation models also predict that there will be weakly nonlinear effects that lead to primordial non-Gaussian signatures in the CMB at some level, but whether the level is such that Planck can observe it is questionable. Canadians have historically been leading in the subject, and are prominent in a new round of action precipitated by WMAP and Planck.

6. THE WEAK LENSING OF THE CMB

Another secondary anisotropy and nonlinear effect is weak gravitational lensing of the CMB by the intervening cosmic web which modifies its propagation to us in an accurately computable way. The complication is that the typical smoothing scale of the primary CMB fluctuations is that associated with the viscous damping scale of the baryon-photon fluid, many arcminutes, so it has a disadvantage relative to the sub-arcsecond galaxy scale. However, we precisely know the source redshift distribution, namely the universe at redshift 1100, and the lensers are at all redshifts below. We also have polarization information to augment the lensing of total anisotropy. With ACTpol and SPTpol, and, indeed, with Planck, we have great hopes for what we will learn in support of our paradigm, in which the CMB structure and large scale structure derive from the same basic underlying theoretical evolution, with impact for unraveling the dynamical nature of the dark energy. There is an LRP white paper on cosmology using the weak lensing of galaxies by the cosmic web, which is quite complementary to the CMB lensing.

7. CMB RELATION TO OTHER DARK ENERGY PROBES: WEAK LENSING, BARYON ACOUSTIC OSCILLATIONS, SUPERNOVAE, AND CLUSTERS

Essentially all cosmic probes require the augmentation by CMB information to restrict the cosmological parameters that they are not that good at measuring. This is true for the four dark energy probes: baryon acoustic oscillations, weak lensing, supernovae Ia and cluster abundances as a function of redshift. Cluster abundances as a function of the thermal energy content of clusters (which is correlated with mass), as determined by the SZ effect, is a CMB subject, as mentioned above. The original BAO detection is of course the CMB acoustic peaks and troughs from redshift 1100. There is an LRP white paper on cosmology using redshifted 21 cm information to probe BAO.

8. CMB THEORY AND ANALYSIS MANPOWER NEEDS

The world has invested heavily in CMB experiments, and the teams involve theorists and analysts/phenomenologists as well as experimentalists. Canada has done very well so far in these, obtaining considerable scientific luminosity, and is poised to play important theory and analysis roles in many of the new leading edge experiments, including in Planck. There is no funding source but NSERC for CMB theory generally and for the analysis of ground-based CMB experiments. CSA supports contract-specific work for Planck and balloon-borne CMB experiments, not general analysis and theory. Obtaining such support has been difficult. Although CSA has been attempting to find other paths of grant support for its funded missions, including programs with NSERC, these efforts are not as yet sustained programs, and there is nothing like NASA theory grants available, nor Hubble, Einstein, Spitzer, ..., Fellowship Programs. Our competitors/collaborators in other countries are able to draw on significant resources to hire the manpower needed to support large team efforts specifically, and theoretical and analysis efforts generally, but for us in Canada it is a struggle. Multi-centre programs providing postdoctoral funding beyond what NSERC Discovery Grants give are essential for Canada to be well positioned to exploit the science in the CMB area.

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