CMB Polarization Measurements: 2015 and Onward

A White Paper submitted by the IPSIG to
NASA's Astrophysics Subcommittee

The Theoretical Landscape

The BICEP2 experiment recently announced a detection of B-mode polarization in the cosmic microwave background (CMB) radiation at angular scales of about 1 degree. The results generated great interest because this is the angular scale in which gravitational waves from the epoch of inflation are expected to imprint a characteristic signature. But uncertainties about the cosmological origin of the signal remain because of uncertainties with the magnitude of emission of galactic dust. The response to the BICEP2 announcement highlights both the scientific importance of, and popular interest in, observational constraints on cosmic genesis. If the BICEP2 measurement contains an inflationary component then it sets the energy scale responsible for the inflationary epoch near $2 \cdot 10^{16}$ GeV, some 13 orders of magnitude above energy scales probed in the largest Earth-based colliders. This in itself would be a stunning discovery, but it would only be the beginning.

A measurement of the energy scale of inflation opens the observational door to a number of problems of fundamental physics:

- Did only a single quantum field drive inflation?
- If so, the value of that field changed by a very large amount, an amount that is larger than the Planck mass. What mechanism or model that emerges from a theory of quantum gravity (e.g. string theory) can explain this "super-Planckian" trajectory? How might we detect additional signatures of these models and probe the effects of high energy degrees of freedom involved in the ultraviolet completion of gravity?
- What are the new symmetries of nature that are hinted at by the BICEP2 discovery?

To approach the last two questions, the next step is to measure the tensor to scalar ratio r and the power spectrum of the scalar perturbations, including the spectral index n_s and its dependence on spatial scale with increasing accuracy. Inflationary models make predictions for these quantities, as well as the level of non-Gaussianity, and increasing precision can help identify the correct class of models. There are plans to reduce the errors on n_s by a factor of five using galaxy surveys, and future CMB polarization experiments should aim to reduce the error on r to the percent level. These percent level constraints, along with further theoretical work to better classify the range of predictions from ultraviolet-complete large-field inflation, will help constrain the model, and therefore the underlying physics, that drove inflation. One basic question is whether a quadratic potential will fit the data, or whether additional structure is required.

Furthermore, with this precision in the measurement of n_s and r the predictions of inflationary models become dependent on the details of the reheating process. Thus these data will also provide constraints on the couplings of the field that drove inflation to the standard model. The high energy scale of inflation implied by the BICEP2 results also implies that constraints on reheating might give us information on extensions to the standard model because one has to make sure no relics are produced during reheating which are inconsistent with measurements of the late Universe.

Single field inflation models make a robust prediction that the spectral index of the *tensor* perturbations n_t is related to the amplitude of those perturbations r. An ambitious goal is to test this prediction. More generally, measuring both the scalar and the tensor spectrum with as much accuracy as possible will probe for deviations from simple inflationary predictions and be sensitive to new ideas for the physics that governs these ultra-high energies.

A Time Line of Measurements

The emphasis in the near future (0-5 years) will inevitably be on conclusively determining the origin of the signal detected by BICEP2. Three observational criteria must be established to provide confidence in its cosmological origin. The signal should have: 1) a frequency spectrum that is consistent with CMB anisotropy and distinct from Galactic foreground emission; 2) an angular power spectrum that is consistent with the cosmological expectation; and 3) it should demonstrate statistical isotropy. In addition, independent measurements of the signal with different techniques, on different platforms, at different frequency bands and angular scales will rule out instrumental systematics as a significant source of spurious effects.

There are a number of experiments that are poised to provide such near term measurements. Figure 1 provides an overview of currently ongoing experiments, their characteristics, status and anticipated time for release of results. The community awaits with interest the release of the Planck satellite polarization results in October 2014. Although according to pre-flight sensitivity estimates Planck should be able to detect a signal at the level measured by BICEP2, the actual measurement is likely to be limited by systematic, rather than statistical uncertainties.

If the origin of the signal is cosmological then the next observational goal (3-10 years), consistent with the theoretical program described earlier, is to constrain the value of r to percent levels. The measurements will require sensitivity per resolution element similar to that achieved by BICEP2, but over the majority of the sky. To survey large portions of the sky, ground based experiments will need to contend with atmospheric noise, which is more acute on large angular scales. To overcome atmospheric noise, experimenters are considering employing rapid temporal modulation. Such rapid temporal modulation of the polarization has already been used by both balloon-borne ground-based experiments. Galactic foregrounds also have more power on large angular scales. Data from Planck will be useful to quantify the level of foreground subtraction that will be necessary to extract the underlying B-mode signal.

A complete characterization of the inflationary B-mode signal (6-15 years), including any information about the spectral index of the *tensor* perturbations n_t, will require at least an order of magnitude increase in sensitivity relative to BICEP2 and mapping of significant portions of the sky with resolution of ~3 arcminutes or better. The high-resolution polarization measurements will be used to de-lens maps, that is, to characterize the contribution of B-modes induced by gravitational lensing of photons as they travel through the large-scale structure of the Universe, and account for this contribution in the estimate of the inflationary B-mode maps and power spectrum. A dedicated satellite mission, such as the one proposed by the CMB community to the NWNH decadal panel, can carry out such a demanding measurement. Although de-lensing has not been demonstrated yet, near term experiments, such as ACTPOL, POLARBEAR and SPTPOL, which have adequate angular resolution, will pioneer the de-lensing techniques within the next few years. They will thus be pathfinders for a future satellite mission.

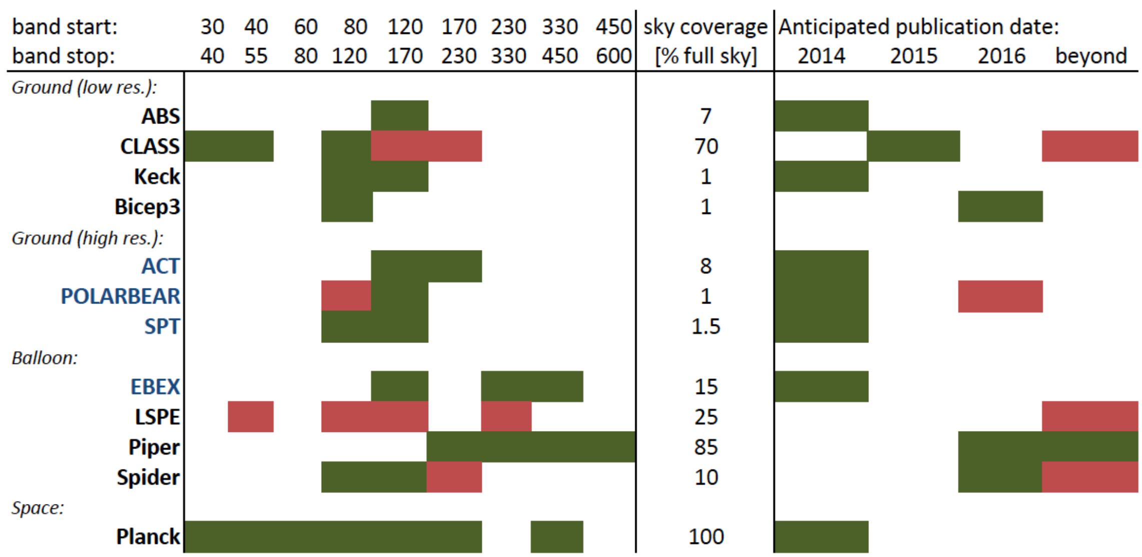

Figure 1: Experimental programs in the field, or soon to deploy, will extend B-mode measurements to other frequencies, a broader range of angular scales, and a larger fraction of the sky. Green and blue colors are for hardware that is built and tested. Red is for built and in testing. The boxes on the right give the anticipated first publication date with colors indicating the corresponding frequency bands at the left. Experiments' names in light blue typeface have an angular resolution that permits de-lensing; black is lower resolution. Sensitivity numbers are not quoted, but all experiments are nominally capable of exceeding upper limits on $r < 0.1$ (the limit derived from large-scale temperature anisotropies) at 2σ.

Space Measurement Opportunities Worldwide

ESA

An ESA call for proposals for a medium-scale science mission is expected in mid-2014, with proposal submission expected toward the end of the year. This is the fourth opportunity within the current ESA Cosmic Vision program, for which previously selected missions are Solar Orbiter (M1, to be launched in 2017), Euclid (M2, 2020) and Plato (M3, 2024). The ESA budgetary envelope of the M4 mission should not exceed about €450-500M, 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. A large European collaboration is at work to submit a proposal for COrE+, an ambitious CMB mission with a science program that will complement the achievements of the Planck satellite. The primary objective of the mission will be to investigate the physics of inflation and to constrain the inflaton potential through precise measurements of the CMB polarization B-modes. Selection of a subset of M4 proposals for a 2-3 year phase-A study is expected in early 2015, a final down select by 2018, and launch after the middle of the next decade.

COrE+ will have an angular resolution of 3-6 arcminutes in the primary CMB channels to enable mapping of the lensing deflection with S/N>1 in individual modes up to $\ell \sim 700$ and de-lensing of the maps. Additional and synergic science goals for CORE+ are the study of the polarization of the galactic ISM, and 3-D tomography of the structures in most of the Hubble volume up to redshift z~few. The 3-D tomography will use the measured CMB lensing, the Cosmic Infrared Background emission fluctuations from high redshift dusty galaxies in the 100-1000 GHz frequency range, and the detection of hundreds of thousands of galaxy clusters observed up to high redshift with the Sunyaev-Zel'dovich effect. The collaboration is investigating adding a high-resolution absolute spectrum measurement capability, but this is currently not within the baseline mission.

The COrE+ collaboration is strongly supportive of a substantive US participation during the proposal stage and, if funded, throughout the mission lifetime.

JAXA

In 2013 the Institute of Space and Astronautical Science (ISAS) at Japan Aerospace Exploration Agency (JAXA) formulated a roadmap for space science and exploration. Under the roadmap, three strategic large JAXA-led flagship science missions are planned within the next ten years, with launch dates in 2015 (Astro-H), 2021 and 2025. The cost cap for these large missions is about $300M, which includes the satellite bus, instrument, launch, and operations. Probing cosmic inflation with the CMB polarization was defined as one of several flagship science topics. LiteBIRD is a proposed space mission that will place stringent constraints on the physics of inflation. It is a candidate for one of the strategic large missions. LiteBIRD will map the polarization of the CMB over the full sky at several frequency bands between 50 and 320 GHz, with a resolution of 30 arcminute (at 150 GHz), and sensitivity of about 2 microK·arcminute. In terms of angular scales, LiteBIRD targets the range $2 \lesssim \ell \lesssim 300$.

In March 2014, the Science Council of Japan (SCJ) published "the Master Plan 2014 for large-scale projects in Japan". The plan represents the recommendations of the research community at large. LiteBIRD is among SCJ's 27 highest priority large-scale projects.

There are more than 70 members from Japan, USA, Canada and Germany in the current LiteBIRD working group. The working group is preparing a mission definition review in 2014-2015 and a system requirement review in 2015-2016. The goal is to be ready for the launch slot in 2021.

The LiteBIRD working group and ISAS/JAXA have sought out international collaborations and are strongly supportive of NASA participation. Specifically, LiteBIRD can benefit from US contributions in detector and cryogenic technologies. A candidate technology for the focal plane arrays is the multi-chroic sinuous-antenna-based pixel, which is under development at UC Berkeley. For the 100 mK cooler, the collaboration is considering a continuous adiabatic demagnetization refrigerator that is being developed at GSFC.

Recommendations

The NWNH decadal panel recognized the importance of detecting and characterizing the B-mode signal calling a detection 'watershed discovery'. It also stated that a discovery of the signal might trigger the development of a space mission to fully characterize the signal. The panel conditioned the beginning of such a development on first finding the signal with sub-orbital measurements. A decadal survey implementation advisory committee (DSIAC), to be convened around mid-decade, was given the task to assess the situation and provide updated recommendations to the funding agencies.

In the nominal NASA budget case, technology development for CMB B-mode measurements was one of two priorities in the mid-scale project category (the other being exoplanet exploration). In the reduced budget case, funding for this technology development was ranked third; developing WFIRST, and technology funding for gravitational-wave and x-ray missions received higher priorities. As a consequence of the funding landscape NASA mothballed any activities toward a future mission, but continued to provide funding for balloon payloads and very limited technology funding through the SAT program. According to current NASA plans the Committee for Astronomy and Astrophysics (CAA) of the National Academies will serve as NWNH's DSIAC.

If the BICEP2 measurement is due to inflationary gravitational waves, then the scenario envisioned by the decadal panel has in fact been realized and NASA can seize the opportunity to assume leadership in probing the physics of the early Universe and at ultra-high energies. But to seize such opportunity requires some actions soon, which can be further guided as more information becomes available. We therefore recommend that NASA embark on the following limited set of low cost actions.

We recommend that NASA initiate a new mission study. The charge for the mission study should include the following items:

1. Determine the benefit of a space mission in comparison to a program of sub-orbital measurements, and quantify the science return from such a mission;
2. Study the observational requirements for extraction of the inflationary B-mode signal and identify mission configurations that perform exciting science at a range of costs and launch opportunities;
3. Identify the contributions that the US community and NASA can provide to a space mission selected either in Europe or Japan;
4. Survey the technological developments since the end of the last decade and prioritize the technologies that are required for a future space mission.

We recommend that planning for the mission study be initiated in the near future such that the study activities can begin in early 2015 after the release of the Planck results.

We note the vast public and science interest in the BICEP2 measurements and their implications. Modest near-term NASA investments in funding for CMB polarization measurements and their associated technologies can make significant impact in advancing the state of knowledge.

We recommend that NASA include the option of significantly increased funding for CMB B-mode measurements when it presents its array of options to the CAA for prioritization.