CMB Polarization Measurements: 2015 and Onward

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The Theoretical Landscape

The BICEP2 experiment recently announced a detection of B-mode polarization at millimeter wavelength and at angular scale 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 (Phase 1) 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 November 2014. Pre-launch cosmological model-dependent sensitivity estimates suggested that Planck would be able to detect a signal at the level measured by BICEP2. Planck's actual performance, on the Universe as it is, will be known in a few months. The Planck and the BICEP2 teams have begun a joint analysis of the BICEP2 field. Combining the low noise of BICEP2 at 150 GHz with the multiple frequency capability of Planck will extract the best constraints on r that can be achieved with existing data. If data gathered in Phase 1 indicate that the signal measured by BICEP2 is of galactic origin then experimental efforts will concentrate on further increasing sensitivity and on better characterization of the galactic foregrounds.

However, if the origin of the signal is cosmological then the observational goal in Phase 2, 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 experiments will need to contend with low frequency noise, which is more acute on large angular scales. To overcome low frequency noise, experimenters are considering employing rapid temporal modulation, which has already been used by both balloon-borne and 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. Flying above most of the atmosphere balloon payloads are immune to atmospheric noise and have access to a broader range of frequencies, albeit at the expense of shorter observation time per data collection campaign. A space mission is an ideal platform for a broad range of frequencies, and access to the entire sky.

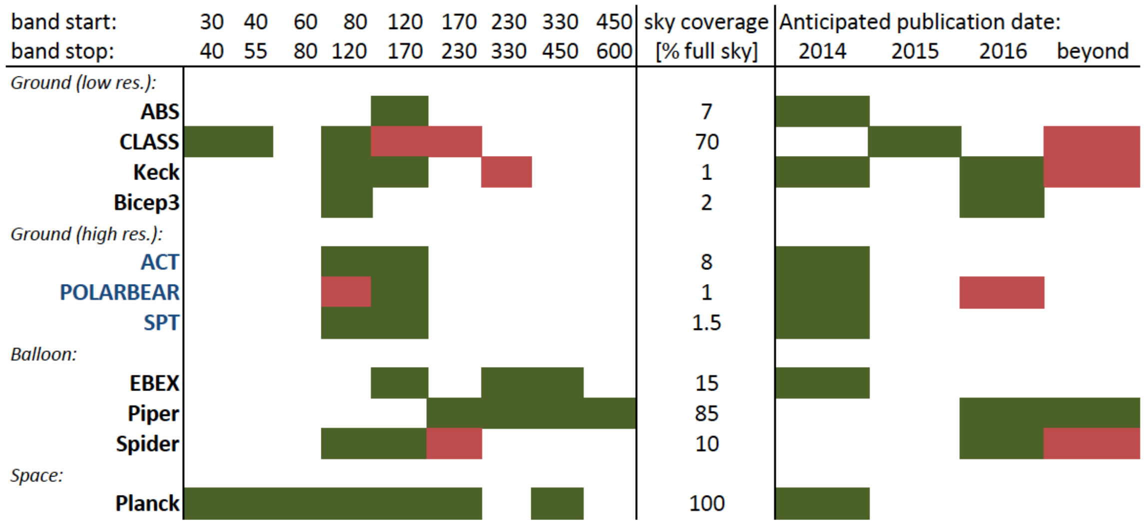

Figure 1: US-based suborbital experimental programs and the Planck satellite, in which the US has a significant contribution, will extend B-mode measurements to other frequencies, a broader range of angular scales, and a larger fraction of the sky. Green colors identify hardware that is in the field, and red indicates hardware that is in preparation. The boxes on the right give the anticipated first publication date with colors matching 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. There are only two European sub-orbital experiments probing B-mode science: the balloon-borne LSPE and the ground-based QUBIC.

Phase 3 of the observational program is dedicated to a complete characterization of the inflationary B-mode signal, including any information about the spectral index of the *tensor* perturbations n_t. Phase 3 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. 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 over small sections of the sky. A dedicated satellite mission, such as the one proposed by the CMB community to the NWNH decadal panel, can carry out the demanding Phase 3 observational program. It has the necessary combination of sensitivity, angular resolution, frequency coverage, access to the full-sky, and control of systematic uncertainties.

Space Measurement Opportunities Worldwide

ESA

An ESA call for proposals for a medium-scale science mission is expected in the fall of 2014, with proposal submission expected near the beginning of 2015. 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 is expected to not 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. 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. A 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 2015, a final down select by 2018, and launch late in 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. International participation is deemed particularly crucial for this round of M4 proposals because of the somewhat reduced funding available from ESA.

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. LiteBird also recently won the endorsement of Japan's Ministry of Education, Culture, Sports, Science and Technology. Every two years the Ministry prioritizes Japan's proposed research projects. In August 2014 the ministry announced that LiteBird is one of 5 projects that received the highest scores for science impact and timeliness.

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.

NASA

NASA priorities for new space missions this decade are to launch JWST, and implement WFIRST as the highest priority recommended by the decadal panel. WFIRST will be a NASA strategic mission with a cost range of $1.5B-$2B. NASA also has a paced program of Explorer missions. An announcement of opportunity for a Small Explorer (PI cost cap of $125M) is expected in late 2014, and for an Explorer (PI cost cap of ~$225M) in 2017. An Explorer mission for a CMB polarization satellite (PIXIE) has already been proposed in 2011.

The NWNH decadal panel recognized the importance of detecting and characterizing the B-mode signal calling detection a 'watershed discovery'. It also stated that a discovery of the signal may 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 eliminated 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 an ad-hoc NRC committee will be established to carry-out the tasks assigned to the DSIAC.

Roadmap

The announcement of the BICEP2 measurements revealed vast public and science interest in CMB B-mode measurements and their implications.

To support Phase 1 of the program described in Section 'A Time line of Measurements' NASA should continue to support measurements of CMB polarization and analysis of the Planck data. While the cost scale for today's instruments, which contain kilo-pixel detector arrays, has increased, the annual APRA funding has not. The same funding levels that used to support experiments with a handful of pixels are now provided for considerably more sophisticated instruments. NASA should recognize this trend and adjust its funding levels for these instruments and for the development of their associated detector technologies. Modest near-term increase in funding through the APRA and SAT grants can make significant impact in advancing the state of knowledge. This is also the recommended course of action should the BICEP2 measurement turn out to be of galactic rather than cosmological origin.

If new data indicate that the measurement is due to inflationary gravitational waves, then a scenario envisioned by the decadal panel has in fact been realized. For this case the panel states that a mid-decade survey panel would recommend whether to start a technology development program with a view to flying a space mission in the next decade. Therefore NASA should include the option of significantly increased funding for CMB B-mode technology program and mission development when it presents its array of options to the NRC for prioritization. Data released within the next 6-12 months should advance our state of knowledge considerably.

ESA's M4 cycle, with proposals due in early 2015, is the earliest opportunity for sizeable US participation in a CMB polarization space mission. There may also be collaborative opportunities with JAXA within the next two years. NASA should enable and support such collaborative activities. It should also maintain financial flexibility to participate in such internationally led mission as the dust settles on whether cosmological B-modes have been detected.

Over the longer term, and again assuming that evidence points to detection of the signature of inflation, NASA should 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. Survey the technological developments since the end of the last decade and prioritize the technologies that are required for a future space mission;
4. Identify the contributions that the US community and NASA can provide to a space mission selected either in Europe or Japan and the scale of funding they would require. (While ESA's M4 opportunity is not commensurate with the time scale of a new mission study, other future opportunities may.)