CMBpol answers to RMS questions
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1. What science can be accomplished with just ground and balloon-based measurements for both anisotropy and polarization? What is the anticipated impact?

   - Sub-orbital experiments will either establish or constrain the energy scale of inflation by searching for the B-mode polarization signal generated by tensor perturbations. If the signal is greater than $r \sim 0.03$, sub-orbital measurements are likely to provide a statistical detection of broadband B-mode power in the coming decade. Other than inflation, there is no known cosmological mechanism to generate a B-mode signal at ell < 100 (the horizon scale at recombination).

     A detection of the tensor signal would be profound since it would give firm observational evidence for inflation, the key physics of the big bang. The amplitude of the tensor signal measures the energy scale of inflation independent of other cosmological parameters. A detection of tensors at $r > 0.01$ would shed light on physics at the Planck scale by informing us that the inflaton field moved over a super-Planckian range during inflation, which is only possible if the theory has a high degree of symmetry. This symmetry requirement could provide a key clue to a final theory that connects quantum mechanics and gravity. An upper limit of $r < 0.01$ would rule out broad classes of inflationary models, in particular those that involve large inflaton field variations.

     While the detection of B-mode power from one or more sub-orbital experiments is likely to be statistically significant, it is unclear how reliable such a measurement would be from the standpoint of foreground rejection and systematic error control. We anticipate a situation analogous to previous generations of CMB experiments: the detection of large-scale anisotropy by COBE, combined with the statistical detection of degree-scale anisotropy by a host of sub-orbital experiments made the case for WMAP and Planck extremely compelling. Similarly, a statistical detection of B-mode power would virtually compel a space-based CMBPol mission because the measurement of the energy scale of inflation is so profound that it requires a measure of confidence that can only be obtained from space: higher sensitivity (above the atmosphere); testable immunity to systematic errors; and access to frequency bands that allow one to optimize foreground rejection.

   - High angular resolution imaging possible from the ground will reveal the effect of gravitational weak lensing through the cosmic shear pattern in both CMB temperature and polarization anisotropy. CMB lensing studies will measure the integrated mass fluctuations out to the last scattering surface at $z=1100$ and also measure the total mass of massive galaxy clusters. Such studies will be complementary to optical lensing shear with galaxy shapes that are sensitive to dark matter out to about z = 2. Lensing of the CMB is a powerful tool because the properties of the lensed source, i.e. the primary temperature perturbations, are better understood than the lensed optical sources resulting in completely different systematic uncertainties for the lensing maps obtained from CMB and optical surveys.

Sub-orbital experiments will constrain the total mass of neutrino species (not mass-squared difference of two states, as in neutrino oscillation experiments) and early (z > 2) dark energy density. The current generation of ground-based experiments, when they are upgraded to measure polarization, will be able to constrain the total mass to ~0.2 eV. Future ground-based polarization surveys within the next decade will do substantially better. CMB Lensing can be studied with just temperature anisotropy but polarization sensitivity greatly improves these studies because it enables the measurement of the effects of cosmic shear on the E-mode polarization. (The effect is also referred to as 'lensing of the E-mode polarization'.) Cosmic shear gives rise to arcminute scale secondary B-mode polarization at angular scales of 200 < ell < 1500 and because of the low cosmic variance on the B-mode signal, is more sensitive. A satellite mission would measure lensing to the cosmic variance limit for ell < 2000 and result in a limit for the sum of neutrino masses of 0.05 eV, similar and complementary to future optical lensing serveys.

- Large aperture experiments from the ground will probe the large-scale structure of the universe as seen in the arcminute angular scale temperature and polarization. The rich science encoded in deviations from the primordial temperature and polarization angular power spectra at these scales has been well studied by the theoretical community with both numerical simulations and analytical methods.

  A wide area survey of the arcminute-scale SZ effect will lead to a mass-limited catalog of galaxy clusters down to 10^{14} solar masses. Such a large cluster catalog will be useful when combined with multi-wavelength galaxy surveys to study galaxy evolution.

  Arcminute-scale anisotropies will be used to measure cluster peculiar velocities with the kinetic SZ signal or to probe the inhomogeneity in reionization through a variety of secondary anisotropy signatures, including those that lead to non-Gaussianities and higher-order correlations.

  Further into the future, SZ polarization will be detected from the ground and will enable ways to establish cluster electron and temperature profiles using the polarization pattern in clusters. Averaged over large samples of clusters, the polarization pattern will reveal the redshift evolution of the primordial CMB quadrupole. This evolution can provide independent information on dark energy.

- Sub-orbital experiments will characterize galactic magnetic fields and their role in galaxy and star formation dynamics. Measurements by different experiments at frequencies between 30 and 1 THz, would yield new information about the properties of galactic dust and synchrotron radiation. Ground-based measurements will be limited to frequencies below ~300 GHz. Balloon-based measurements can probe higher frequencies and can attain a resolution of sub-arcminute close to 1 THz.

2. Does the funding profile change the mix of technology development and measurements if there is not a satellite mission this decade? How can one be sure the costs are correct when there are so many different projects?

    The cost profile in the program report has been generated starting with a poll of current funding in the field. The current projects were carried forward to their projected end. New funding for future new ground-based receivers and balloon experiments was assumed. Technology and detector development at NASA centers, universities, NIST and DOE labs was estimated from current levels and carried forward through the decade with an increase for "mission detectors" in 2017. The numbers are approximate and the profiles are notional. The profiles have not been negotiated with or agreed to by the respective funding agencies.

    The cost profile is based on the model that has delivered remarkable science over the last three decades. Technology development grants and sub-orbital experiments that are competitively selected through the standard refereeing process pioneer new technologies and implement them on instruments that are motivated by current open science questions.

    The previous three decades with a similar number of experiments has served to explore many types of experiments and push forward technology that has ultimately also been used in other fields. These experiments have served as a fertile ground for initiating three ground-breaking satellites. The field has operated in a type of competitive 'market' model. We are advocating that the level of funding would remain roughly constant, and that the forces of the science 'market' continue to shape its future in terms of the number of projects and their potential science return.

    Concerning the ratio of technology to measurement funding, in the absence of unforeseen developments, it should remain roughly as it is now. New technology is the seed for new instrumentation. A shrinking of the technology development budget with an increase in experiment would starve the current growth in the rapid sensitivity gains. Shrinking the experiment support too far would have the effect of leaving too little testing in real experiment systems and potentially squeezing down on a generation of graduate students and young scientists with sufficient hands-on experience to really understand the measurements.

An important exception to the 'market' model is the large-scale technology development that will ultimately be necessary to reach the inflation signal from any platform. Both space and suborbital experiments will require technology development on scales only available at national labs. Labs capable of technology on this scale have been largely supported by detector development funds for the Planck Satellite, other technology for potential future satellite missions, and a smaller amount of support from ground-based projects. In the absence of a future satellite, the sub-orbital program alone cannot support the needed technology development. The large-scale technology development will need to be supported either by the promise of a future satellite or by some other explicitly formulated program. Free standing science-driven technology development programs have disappeared from NASA and been difficult to establish.

The interest of NASA, the major supporter of technology development for the CMB, including detectors and coolers, is quite directly tied to future space missions. Almost all of the support for NASA centers and much of the university technology support comes from NASA. In the absence of a satellite mission on the horizon, the support for the technology foundries at Goddard and JPL and other NASA supported technology development will be in question.

Probing inflation will remain a fundamental and strong science goal. The sub-orbital experiments reaching for that goal will necessarily, by virtue of needing to be more sensitive, be more ambitious and more complex quite aside from the technology development at the national labs. The number of independent large sub-orbital experiments may decline but their individual cost will grow. If a satellite is not on the horizon, a number of these large suborbital experiments will be sufficiently compelling to be funded.

It is important to note that future experiments funded in a ‘no-satellite environment,’ no matter how ambitious, do not replace a definitive satellite measurement. Even considering sensitivity alone, it would take many experiments and many years to generate results equivalent to those of WMAP or Planck using sub-orbital experiments. Ultimately, sub-orbital experiments can never replace a space mission in terms of systematic uncertainties in the final result.

3. If the funding had to be split between ground and balloon-based, what would be the split?

Balloon-borne and ground-based research offer very different advantages for CMB measurements. Unique to ground-based measurements is resolution. Neither balloons nor space platforms are going to provide apertures larger than ~3 meter in the near future. Such large telescopes are currently deployed on the ground and are providing resolution close to one arcminute. This is most important to measure the shear (lensing) signal. The inflationary B-mode signal becomes smaller than the lensing signal for r<~0.02. For smaller values of r and neglecting foregrounds, the lensing signal may limit the level to which the inflationary signal can be measured. Lensing reconstruction, a method not yet fully explored, will rely on the highest possible resolution to remove the lensing B-mode signal. When measurements become sensitive enough to require highly accurate lensing removal, ground-based measurements will be required.

Balloons on the other hand share with space platforms a nearly unlimited choice of measurement frequency, including those not accessible from the ground above 300 GHz. They have unique ability to characterize and remove the polarized emission from galactic dust, a source of foreground about which very little is known. Balloon-borne experiments provide a test-bed for technology development. The high-altitude environment tests thermal models and serves to increment the TRL level for instrumentation.

As the launch of a future space mission approaches, we expect a market-driven rearrangement in the types of sub-orbital experiments being proposed and funded. The high frequency advantage of balloon measurements will be superceded because high frequencies will be measured from space. Similarly, large angular scale B-mode experiments from the ground will no longer be compelling. However, the life time of sub-orbital projects from proposals to science results is short enough to allow the science market to decide. In the future, if a compelling proposal can be fielded, even with a satellite mission approaching, we should not now prejudge the situation.

Finally, this question cannot be answered without remarking about the traditional separation of the funding sources for suborbital experiments. NSF has funded nearly all ground-based experiments and NASA has supported essentially all ballooning with very limited NSF support for ballooning from Antarctica.

4. Even the ground-based program is quite costly on a decade long basis for ground-based programs. If the ultimate answers depend on a space project, how can you justify the funding going into ground-based observations (as opposed to technology development)?

    There are two quite separate answers to this question. First, and most important, is that sub-orbital measurements produce extremely compelling results that compete successfully with other science areas. Many of the ground breaking results in CMB research over the last three decades have been produced or initiated by sub-orbital experiments. deBernardis, Lange, and Richards received the Dan David Prize for measurements done with the balloon-borne Boomerang and MAXIMA experiments.

    It is the success of sub-orbital measurements that served to inspire three satellites. The experiments that resulted in the Nobel Prize for John Mather and George Smoot for the measurement of the CMB spectrum and for the detection of CMB anisotropy each were essentially sub-orbital experiments before they were moved to a space platform (COBE) for the definitive prize-winning measurement.
    In addition, as described above under Question one, sub-orbital measurements have unique role in areas of science that will not be reachable by a satellite. Potential returns include deeper understanding of galaxy formation (through measurements of the SZ effect) and of the reionization history of the Universe; potential discovery of non-Gaussianities; and improving constraints on dark energy. Measurements of polarized dust by balloons may yield valuable information about galactic magnetic fields long before a future satellite. The sub-orbital CMB experiments have produced and will continue to produce science second to none.

    The second answer is that the competitive funding for sub-orbital experiments is likely to be the best and least expensive method of exploring a wide range of technologies and knowledge of foregrounds which ultimately lead to a space-based, astrophysically limited, determination of the B-mode angular power spectrum. No amount of lab development can supplant actual deployment and use of technology in actual measurement. In extracting a science result the technology and instrumentation becomes much better understood. Unexpected non-idealities best become apparent with real science analysis. The integration of the technology into a system is quite distinct from technology development in a lab setting. Many system-level issues are only discovered and resolved in science experiments before being implemented in a satellite.

    However technology development independent of building experiments is necessary for four reasons. 1) Some technology such as cooling and very low background detectors are only needed for space. 2) Some technologies are beyond the ability of a single experiment to support. High pixel-count focal-planes are an example. Independent detector development support is needed which will go into more than one instrument. 3) A small level of support for keeping track and comparing of the progress of different technologies is needed. 4) As the detail of the design of a future mission matures, some of the needed technology is likely to lag behind. A project office should be in a position to determine where additional support is needed and direct technology development support should be identified.