Astro2020 Science White Paper

Unique Probes of Reionization with the CMB: From the First Stars to Fundamental Physics

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☒ **Cosmology and Fundamental Physics**
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☒ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Summary:
Much of reionization remains hidden from view, and along with it our understanding of how stars, black holes, and galaxies first emerged from the afterglow of the big bang. The CMB is among the most powerful ways to probe this remote epoch and answer fundamental questions in cosmology and astrophysics. In particular, several classes of secondary CMB temperature and polarization anisotropies are sourced directly by reionization through Thomson scattering. We outline the range of scientific discoveries about reionization enabled by observations of these CMB secondary anisotropies possible in the coming decade, and highlight the some of the most difficult challenges, including planning and coordination, frequency coverage, angular resolution, and sensitivity.

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Why Study Reionization?

Reionization is believed to have occured when the earliest generations of stars and black holes emitted a sufficient amount of UV and X-ray radiation to ionize the vast majority of neutral hydrogen in the universe in the first bilion years of cosmic history. Thus far only a handful of extremely bright sources have been detected from reionization, and little is understood about the process itself. Studying reionization allows us to answer outstanding questions in two broad areas; fundamental physics and the emergence of complexity.

Fundamental Physics

Dark Matter and Inflation – During reionization, density fluctuations at a given scale were much weaker than at present, and gravitational instability can be modeled to much smaller scales, increasing the dynamic range available to probe the scale-dependence and Gaussianity of inflationary perturbations, and to distinguish between dark matter candidates through their effect on the small-scale power spectrum and abundance of collapsed structures.

The Neutrino Mass – The overall normalization of primordial density fluctuations as constrained by CMB primary anisotropies, A_s, is degenerate with the Thomson scattering optical depth to reionization, τ, which acts to suppress primary anisotropies over a wide range of angular scales. This degeneracy of initial matter perturbation amplitude with the optical depth represents a major source of theoretical systematic uncertainty for Stage-IV measurements of the sum of the neutrino masses.

Emergence of Structure

The First Galaxies and Supermassive Black Holes – In the same way that ionized regions in the nearby universe are laboratories to study star formation, the history and morphology of reionization, as probed directly with the CMB via Thomson scattering, is a laboratory for understanding how the first stars, galaxies, and black holes emerged from the cosmic dark ages, in particular their evolving abundance, composition, and mass distribution.

The Thermal Memory of the Intergalactic Medium – An immediate consequence of reionization is the heating of the intergalactic medium from a temperature of $\lesssim 10$ K to $\sim 10^4$ K, with dramatic consequences for the post-reionization universe. In particular, the Lyman-α forest and spatial distribution of low-mass galaxies *after reionization* depend on the complex pattern of percolating ionized bubbles that can be constrained with next-generation CMB temperature and polarization measurements.

The CMB is a Powerful Probe of Reionization

The CMB is a unique probe of reionization because scattering of photons by free electrons affects the observed temperature and polarization in a predictable fashion that is sensitive to its duration, patchiness, or both. There are three main ways in which this occurs.

Large-angle E-modes

Thomson scattering induces a linear polarization in the direction perpendicular to the scattering plane, leaving the net amount of polarization proportional to the quadrupole of the incident radiation field. During reionization, this quadrupole varies on scales corresponding to the size of the horizon, subtending tens of degrees and leaving a predictable feature in the polarization E-mode power spectrum known as the "reionization bump" on very large scales. Given the difficulty in measuring polarization on such large scales from the ground, the only detection of this effect has been made from space, first by WMAP and then by Planck. The most recent analysis by Planck constrains the Thomson scattering optical depth to be $\tau \simeq 0.06 \pm 0.007$, and is the most direct information about reionization currently available.

Patchy kSZ

The kinetic Sunyaev-Zel'dovich (kSZ) effect is caused by the Doppler shifting of primary CMB photons as they are Thomson scattered off of moving electrons. A key aspect of the kSZ effect is the generation of small-scale temperature anisotropies by coupling large-scale velocity perturbations with the patchiness of the ionized field on small scales. While the kSZ effect has long been recognized as one of the most promising probes of the intergalactic medium during and after reionization (e.g., Sunyaev, 1978; Kaiser, 1984; Ostriker & Vishniac, 1986), it has begun to be used only recently to provide constraints on reionization, in particular on the duration (e.g., Battaglia et al., 2013), through the analysis of the angular power spectrum of the CMB temperature at $\ell \approx 3000$ (Reichardt et al., 2012; Zahn et al., 2012; George et al., 2015; Planck Collaboration et al., 2016).

Patchy Screening & Scattering

Aside from Doppler shifting, variations in the optical depth due to patchiness manifest in two additional ways. First, they screen the primary CMB, sourcing new anisotropies that are proportional to the product of the optical depth and primary anisotropies. Second, scattering generatas polarization anisotropies that are proportional to the product of the optical depth and primary intensity quadrupole at reionization. The modulation of primary anisotropies from the screening effect is similar to gravitational lensing and, with sufficient sensitivity and resolution, optical depth fluctuations can be reconstructed using techniques similar to those used in CMB lensing reconstruction (Dvorkin & Smith, 2009; Dvorkin et al., 2009). The scattering effect is detectable as an additional source of polarization E and B-mode power, but cannot be used to reconstruct the optical depth unless the quadrupole at reionization, which is very difficult to measure otherwise, is known.

Breakthroughs in the Next Decade

In the next decade we will witness significant gains in detector count, sensitivity, and survey area from the ground, first from Simons Observatory and then CMB-S4, while proposed space missions such as LiteBIRD and PICO have the potential to measure the polarization of the CMB over nearly the full-sky with an exquisite control over systematics.

Precision Reionization Constraints with the kSZ Effect

CMB experiments in the next few years will likely make robust detections of the kSZ effect through the temperature power spectrum and constrain the duration of reionization to roughly 10 percent accuracy (e.g., Calabrese et al., 2014; The Simons Observatory Collaboration et al., 2018). Looking further into the future, a ground-based experiment such as CMB-S4 could provide definitive reionization constraints from the high-ℓ CMB, due to its higher sensitivity and ability to probe both the kSZ power spectrum and four-point function, the latter of which provides a robust way to separate early- and late-time kSZ contributions (Smith & Ferraro, 2016; Ferraro & Smith, 2018). Realistic forecasts indicate a CMB-S4 patchy kSZ measurement can improve the current *Planck* EE-based τ constraint by a factor of more than three, possibly exceeding the precision from a cosmic variance limited EE measurement at large-scales.

Probing Cosmic Dawn with Large-Scale E-modes

The Thomson scattering optical depth is useful as an overall constraint on reionization, and measurement of the E-modes to cosmic variance limit at $\ell \lesssim 50$ remains a major challenge in cosmology. Currently the Cosmology Large Angle Surveyor (CLASS) is attempting just such a measurement, which is a significant test for the viability of large-angle polarization measurements from the ground. Additionally, proposed space missions such as LiteBIRD or PICO could provide near CVL measurement at $\ell < 50$ with better control of systematics from space. A cosmic variance limited EE observation at $\ell < 50$ would provide finer-grained resolution on the optical depth evolution than Planck and, in particular, constrain the early reionization 'tail' (Heinrich & Hu, 2018) which would place significant constraints on theories of early star formation, including X-ray binaries and massive Population III stars (e.g., Miranda et al., 2017).

Measuring Patchiness with Precision Polarization Maps

The unique B-mode signature of patchy reionization could provide us with unique insights into the reionization history as well as the sources that produced the ionizing photons. More detailed modeling is necessary for detailed forecasts, but the existing literature indicates that the exquisite polarization sensitivity of Stage IV experiment or space-based mission focused on measuring B-modes at the level of $\sigma(r) \sim 10^{-3}$ at $50 \lesssim \ell \lesssim 500$ will constrain the morphology of reionization over a broad range of scales and allow us to test models in which large bubbles surround relatively rare sources Roy et al. (2018).

Cross-correlation Enabled Reionization Science

Reionization will be observed with several complementary probes. Most prominently, 21cm experiments allow us to make 3D maps of the evolution of the neutral hydrogen density. While the high spectral resolution of 21cm observations provide line-of-sight information, CMB measurements place integral constraints probing variations on $\Delta z \gtrsim$ a few. Cross-correlations not only bring together complementary information, but may also alleviate some of the foreground challenges in 21cm, resulting in a more robust and detailed constraint on the global ionization history. In addition, intensity mapping experiments and galaxy surveys, targeting CO, CII, Lyman-α and other atomic and molecular emission lines, all trace the underlying matter distribution.

Patchy kSZ

The kSZ signal encodes information both about the large scale fluctuations as well as the small scale patchy electron density, and therefore should be correlated with other tracers of of LSS and patchy reionization. The synchrotron foregrounds for the 21cm observation are spectrally smooth in frequency range which contaminates the radial modes with small wavenumber (i.e $k_{\parallel}$). By applying tidal reconstruction techniques it is possible to recover those lost large scale radial modes in foreground and hence, it could be possible to detect the cross-correlation signal of kSZ and 21 cm (Zhu et al., 2018; Li et al., 2018). Other tracers of the large scale velocity field such as LAEs and CO/CII are less likely to suffer from contamination of foreground contamination into projected line of sight modes than 21cm, and so there is the possibility that velocity reconstruction from the biased tracers δ_g or, equivalently, the bispectrum $\langle \delta_g \delta_g T \rangle$, will be measured directly. However, CO/CII intensity mapping is difficult to obtain over as large a fraction of the sky, leaving 21cm as the most promising probe to correlate with in the near term. Space-based missions capable of Lyman-α intensity mapping over a large fraction of the sky are being considered (e.g., Cooray et al., 2016), and would likely produce a data set ideal for cross-correlation.

Patchy Polarization

Previous analyses (Gluscevic et al., 2013; Namikawa, 2018) have shown that it is quite difficult to detect the patchy reionization signature in the B-mode power spectrum alone. Recent work, focusing on using cross-correlations with external Large scale structure tracers Feng & Holder (2018a), is more promising. Tracers such as galaxies and the cosmic infrared background are cross correlated with reconstructions of the optical depth (τ). Numerical calculations show that next-generation CMB experiments will be able to detect a $\langle \tau \Psi \rangle$ cross correlation, however, it mostly contains information from the late Universe, and the high-z contribution is subdominant. Higher order statistics based on the trispectrum have been shown to be very promising for separating out the patchy reionization component, with forecasts indicating that the cross power spectrum will be robustly detected using future data from next generation CMB experiments (Feng & Holder, 2018b). Additionally, it is possible to correlate polarization anisotropies induced by patchy reionization with other tracers of large scale scale structure such as the cosmic infrared background and CMB lensing Feng & Holder (2018a,b).

Challenges for the Road Ahead

The breakthroughs in CMB-enabled reionization science outlined above are within reach, but only if substantial theoretical and experimental challenges are met, particularly in planning and coordination with other reionization probes, frequency coverage, angular resolution, and sensitivity.

Multi-wavelength Survey and Analysis Coordination

Data from experiments targeting reionization at other wavelengths will be highly synergistic. In particular, instruments capable of probing reionization over large areas of the sky ($\gtrsim 10^3$ deg^2) already taking data or in various stages of planning, such as radio interferometers targeting 21-cm emission and futuristic ground and space based galaxy surveys and line intensity mapping experiments, will make cross-correlation reionization science in the next decade a realistic possibility.

Exploring cross-correlation and joint analysis with 21cm data is a very promising avenue in both the near and long term. Coordination between the CMB and 21cm communities should extend from survey planning through to analysis, specifically by maximizing survey overlap and adopting physically consistent reionization models that account for correlated systematic modeling uncertainties. It will be highly desirable for 3D tomographic 21cm maps to be made available for subsequent cross-correlation with CMB maps and for significant effort to be dedicated to the development of advanced analysis techniques that can be tailored to individual experiments, including higher-order correlations and joint forward modeling. Such coordination is crucial if we are to use our knowledge of reionization to improve the precision of cosmological parameters such as the mean optical depth and neutrino mass.

Sensitivity, Frequency Coverage, and Foregrounds

Polarization anisotropies can provide crucial information on reionization, but polarized Galactic and extragalactic foregrounds and instrumental systematics will need to be characterized and understood with a very high accuracy. In addition, the patchy reionization signal could potentially be a nuisance in B-mode searches for primordial gravitational waves, depending on how large the effect is (e.g., Roy et al., 2018). Both of these considerations motivate a careful study of techniques to jointly model and separate the effects primordial gravitational waves, patchy reionization, and polarized galactic and extragalactic foregrounds.

The kSZ effect has significant potential to reveal a great depth of information about the morphology and duration of the reionization process, but much of the information is at small angular scales, $\ell \gtrsim 3000$, where the primary fluctuations are suppressed. At these scales, other contaminants such as the thermal SZ effect and cosmic infrared background (CIB) dominate. The requirements to extract most of the information from the kSZ are quite stringent: a resolution of $\sim$1 arcmin with a noise level of $\sim$1 μK-arcmin, to probe the rich angular structure imprinted by the ionized bubbles, and multiple bands at frequencies $\gtrsim 150$ GHz, to minimize noise and measurement bias from contamination by foregrounds such as the thermal SZ effect and CIB.

The CMB will continue to be an indispensable source of information on the epoch of reionization, and is likely to play a pivotal role as we finally begin to map out its structure and evolution and answer longstanding questions about fundamental physics and how complexity first emerged.

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