Resolving high-redshift clusters with the Sunyaev-Zel'dovich Effect and MUSTANG

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Abstract

The Sunyaev-Zel'dovich Effect (SZE) is a predominately thermal distortion caused by the inverse Thompson scattering of cosmic microwave background (CMB) photons by high energy electrons, such as those found in the intra-cluster medium. Because it results in an average energy shift in CMB photons that is independent of redshift, it is a valuable tool to observe very distant galaxy clusters, and in recent years several blind surveys have made use of it to locate a catalogue of these clusters. MUSTANG is a 90GHz, 9"-resolution bolometer camera on the 100m Green Bank Telescope (GBT). Its large dish and high angular resolution make it a well-suited instrument for observing a variety of objects both inside and outside the galaxy. We propose to use MUSTANG to examine several of these survey clusters in more detail, providing spatially-resolved measurements in order to provide the first images of their structures. With redshifts of $z > 1.5$, the chosen clusters are some of the most distant collapsed objects yet observed, and so may provide insights into the nature of primordial perturbations in the density field of the early universe.

1 Scientific Motivation

1.1 Early cluster formation

Over the past several decades, observations of the cosmic microwave background (CMB) have investigated and supported the model of an inflationary universe, with structure formed from primordial adiabatic perturbations[2]. If the sole sources of these perturbations are quantum fluctuations in the scalar field of inflation, the distribution of primordial density perturbations should be expected to be nearly perfectly Gaussian, and so measurements indicating non-Gaussianity would point towards the presence of a second scalar field

Cluster	z	R_{500} (Mpc)	M_{500} ($10^{14} M_{sun}$)	$k_B T_e$ (keV)
RX J2596-5844	1.56±	1.41	16.4	10.5
SPT-CL J5306+4487	1.62	1.39	15.2	11.1
MACS J1204.2+7747	1.90	1.28	10.4	13.2
MACS J3006.6-3195	1.71	1.07	9.1	12.6
SPT-CL J1947-5623	1.59	1.53	17.2	10.9

Table 1: Cluster properties (x-ray derived) from Smith et al., 2013.

(a multiple-scalar-field model of inflation[3]), or that such perturbations derive from topological defects or other exotic mechanisms[4]. Key observables for such measurements include maps of the CMB itself, large structure in the present-day universe, and properties and statistics of massive high-redshift objects.

Among the most massive objects in the universe, consisting of hundreds or thousands of galaxies gravitationally bound to each other, galaxy clusters fall within this last category. Forming from overdensity perturbations in the very early universe, galaxy clusters found at high redshifts in particular provide valuable insight both into the mechanics of their evolution as well as into constraints on the Gaussianity of the primoridal perturbations of the density field.

As such, the clusters identified in this proposal are all among the farthest ever detected (see Table 1 below for cluster details). Comprised of approximately 85% dark matter, a few percent stars, and around 12% hot intracluster plasma, these clusters are also unusually massive objects to have coalesced at such an early point in the universe's history. To understand how these objects could have formed, their origins, and their evolution, it is critical that higher resolution measurements be made of each.

1.2 Sunyaev-Zel'dovich Effect

It is the hot plasma that occurs between the galaxies inside the clusters that is the primary observable relevant to this proposal. Termed the intracluster medium (ICM), the electrons in this hot gas preferentially boost the energy of the background CMB photons through inverse Compton scattering, resulting in a small spectral distortion called the Sunyaev-Zel'dovich Effect (SZE). This distortion, seen as a decrease in the intensity of the CMB at frequencies below $\sim$ 218GHz, is directly proportional to the electron number density in the ICM along the line of sight, and, critically, is independent of redshift[1]. These properties make it a valuable tool to image galaxy clusters in general, but particularly at high redshifts, where other imaging techniques struggle to attain the required sensitivity. High resolution SZE measurements allow the determination of structure in clusters even at the highest redshifts, and therefore represent the best method currently available to investigate the physical properties of these distant clusters.

2 Technical Justification

As a high-resolution, large collecting area bolometer array observing at 81-99GHz, the Green Bank Telescope's (GBT's) MUSTANG[5] camera is uniquely suited to make observations of these clusters. Its angular resolution of 9" and 100m dish allow for both strong sensitivity and a high level of detail. With a characteristic scale size on the order of one megaparsec, galaxy clusters range in angular size from degree-scale for nearby clusters, to arcminutes or more at appreciable redshift. The regions used to image the clusters discussed in this proposal will be square, 5' by 5', large enough to comfortably contain the extent of each object along with some of the background, for differentiation.

[h]

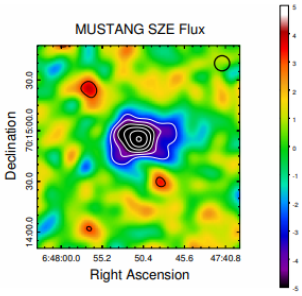

Figure 1: An SZE image of a galaxy cluster, MACS J0647.7+7015, imaged using MUSTANG. The black circle illustrates the size of the 9" beam, with white contours shown in increments of 1-σ above $3-\sigma$ (SZE signal), and black contours for positive flux.[6]

Conditions required to make these observations include clear, nighttime skies (as variable daytime temperature gradients in the telescope's structure interfere with its performance in the 90GHz band), with low levels of precipitable water vapour[8]. To determine focus, calibrator sources will be checked on a range of focus settings every 30 minutes throughout each observing session. We expect that these focus corrections will remain stable to the millimeter level over several hours, under these conditions.

For each region, a 'daisy' (Lissajous) scan pattern will be used in combination with a 'box' scan pattern. The Lissajous scan, with seven pointing centres near the cluster cores, provides intensive, uniform coverage that falls off beyond 30"[6], while the box pattern moves at a roughly constant pace and provides flat coverage over the rest of the square region. Moving slowly (<1' per second) allows redundant imaging of each point in the sky (as well as eliminating the risk of stressing or exiciting resonances within the structure of the GBT), enabling significant removal of noise on the timescale of a source moving between pixels (between 0.07s to 0.5s[5]). The scan patterns also allow controlling for $1/f$ noise on scales $> 5s$, according to the spacing of observations of the same points on the sky. The expected effective collecting area at this frequency is approximately 20%, so we expect a gain of $0.2\pi(50m)^2/(2k_B)$ K, or $\sim$0.5K/Jy^{-1}. For a precision level on the order of 0.1mK (the fluctuation in the CMB temperature caused by the SZE is generally $\sim$1mK), the observation time per beam must be at least $B^{-1}(T_{sys}/\delta T)^2 = 2$s. Therefore, for each 5' by 5' region, the observation time will be 1200s (0.33 hr), plus 0.5 hr overhead for calibration and orientation. For all five clusters, therefore, the total requested time is 4.5 hr.

References

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