BICEP2 and Keck Array: upgrades and improved beam characterization

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[1]

ABSTRACT

Finding evidence for inflation by detecting B-modes in the cosmic microwave background (CMB) polarization at large angular scales remains one of the most compelling experimental challenges in cosmology today. BICEP2 and the *Keck Array* are part of a program of experiments at the South Pole whose main goal is to achieve the sensitivity and systematic control necessary for tensor-to-scalar ratio $r \lesssim 0.01$ measurements. Beam imperfections that are not sufficiently accounted for are a major potential source of spurious polarization that could interfere with that goal. The strategy of BICEP2 and *Keck Array* is to completely characterize their telescopes' polarized beam response with a combination of in-lab, pre-deployment, and on-site calibrations. We report the status of these experiments, focusing on continued improved understanding of their beams. Far-field measurements of the BICEP2 beam with a chopped thermal source, combined with analysis improvements, show that the level of residual beam-induced systematic errors is acceptable for the goal of measuring $r \sim 0.01$. Similar measurements have been made for the *Keck Array.* On-site measurements of *Keck Array* showed unexpected side lobes that were terminating on the absorptive telescope forebaffles. Follow-up lab measurements confirmed these side lobes were due to inadequate blackening of the cryogenic telescopes. Although terminating these side lobes on the forebaffles strongly reduces the possible systematic error impact, it does contribute to the optical loading because the forebaffles are warm. Therefore, in late 2013 the five telescopes were upgraded on site with improved interior cold baffles. These baffles have substantially reduced total optical loading, leading to a $\sim 10\%$ increase in mapping speed for the 2014 observing season. The sensitivity of *Keck Array* continues to improve: for the 2013 season it was $9.5\,\mu\mathrm{K}\sqrt{\mathrm{s}}$ noise equivalent temperature (NET). In 2014 we converted two of the 150-GHz cameras to 100 GHz for foreground separation capability. The combined sensitivity at 100 GHz is $17.4\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. We have shown that the BICEP2 and *Keck Array* telescope technology is sufficient for the goal of measuring r at the 0.01 level. Furthermore, the program is continuing with BICEP3, a 100-GHz telescope with 1280 dual-polarization pixels.

Keywords: Inflation, Gravitational waves, Cosmic microwave background, polarization, BICEP2, Keck Array.

1. INTRODUCTION

Measurement of cosmic microwave background (CMB) polarization is one of the most successful probes of the inflationary epoch of the early Universe. BICEP2 and the Keck Array are part of a series of experiments whose goal is to measure the degree–angular-scale B-mode (odd-parity) polarization predicted by inflation. Cosmologists parameterize the amplitude of the inflationary signal by the tensor-to-scalar ratio, r. We reported results from BICEP2 including a measurement of $r = 0.20^{+0.07}_{-0.05}$.[1] Telescope beam imperfections are a potential source of systematic error. Therefore, we have a strategy of completely characterizing the polarized beam of each experiment followed by reducing the spurious polarization effects in analysis. Keck Array is still observing, and we continue to make improvements to it. These proceedings discuss upgrades made for the 2013 and 2014 seasons of Keck Array and the status of beam characterization for both experiments.

The inflationary paradigm, by positing an exponential expansion of the early Universe ($< 10^{-32}$ s), sets the initial conditions for the hot big bang. Inflation is compelling because it naturally solves the flatness, horizon, smoothness, entropy, and monopole problems of standard cosmology.[2] Furthermore, inflation explains the initial perturbations of the Universe as quantum fluctuations that were stretched by the exponential expansion. A unique prediction of inflation is the production of a stochastic background of gravitational waves. The presence of these gravitational waves at the CMB last scattering surface results in an curl-type (B-mode) polarization pattern

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at degree angular scales.[3] (Gravitational waves also generate E-mode polarization, but the inflationary E-mode signature is much smaller than the E-mode polarization from density perturbations. Density perturbations do not produce B-mode polarization.) The amplitude of this pattern is proportional to r, which is also proportional to the energy scale at which inflation occured. Measuring this signal is the main science goal of BICEP2 and the Keck Array.

BICEP2 and *Keck Array* are part of a series of experiments at Amundsen–Scott South Pole Station whose main science goal is to measure the B-mode signal from inflation. The experiments share many aspects of their design. Both use small (26-cm) aperture cryogenic refracting telescopes. Absorbing, ambient-temperature forebaffles block potential pickup of the ground or Galaxy. The detectors are planar arrays of antenna-coupled transition-edge sensor (TES) bolometers. BICEP2 has 512 such bolometers in its focal plane, and they are paired into 256 pixels where each pixel has two bolometers with orthogonally polarized antennas. *Keck Array* has five BICEP2-style receivers in a close-packed configuration. Both experiments have three-axis mount systems; we refer to rotation around the telescope boresight as "deck" rotation. More details about the instruments are in previous publications.[4,5]

The inflationary signal is very small compared to potential contaminating signals such as the CMB temperature fluctuations, Galaxy, and ground. Beam imperfections, particularly mismatches between the two detectors in the same pixel, can create spurious polarization and contaminate the B-mode measurement. Section 2 covers characterization of the BICEP2 and *Keck Array* beams, including the measurements leading to the limit on BICEP2 beam-induced systematic errors at $r \lesssim 0.001$. We continue to improve the sensitivity and instrumental control of systematics of *Keck Array*. Section 3 covers improvements in sensitivity, differential pointing, forebaffle loading and the addition of 100-GHz receivers.

2. IMPROVED BEAM CHARACTERIZATION OF BICEP2 AND KECK ARRAY

We have previously reported beam characterization of BICEP2[6] and *Keck Array*.[7] Since then we have made higher–signal-to-noise beam measurements with a brighter microwave source and improved the corresponding analysis techniques. We have applied the same beam measurement improvements to *Keck Array*. Finally, we have improved our understanding of the far side lobes of the beams.

2.1 BICEP2 Main Beam Characterization

We measure the BICEP2 optical response of each detector in the far field in situ with artificial microwave sources. Using this setup we make multiple maps of each detector's beam. We analyze and model the beams, including the mismatch between orthogonal detectors in the same pixel. The resulting maps and models inform simulations of the systematic effects of beam imperfections on the measurement of r.

The far-field beam mapping setup consists of a microwave source and flat mirror to redirect the radiation into the telescope (Figure 1). For the measurements described in this section, the source is a thermal chopper: Rotating blades, covered in Eccosorb microwave absorber, alternately present ambient-temperature ($\sim 250\,\mathrm{K}$) or sky ($\sim 15\,\mathrm{K}$) radiation to the telescope (Figure 2). A flat mirror behind the chopper blades redirects sky radiation from zenith. The typical rotation frequency of the chopper is 18 Hz. Compared to previous measurements, the active source aperture is larger (20-cm diameter). (We used a broadband amplified noise source for some measurements, see Section 2.3.) We mount the source on top of a 10-m tall mast, 211 m away from the telescope. A flat mirror mounted directly above the telescope allows it to observe the source.

Using this setup we make maps of each detector's beam by scanning the telescope over the source in azimuth and elevation. We repeat the mapping procedure at multiple deck angles to confirm consistency and repeatability of the results. We then combine the data from all deck angles (Figure 3). The combined maps reflect the expected main beam shape, Airy rings, and known cross-talk features (primarily due to cross talk in the readout system).

We construct an elliptical Gaussian beam model based on the map of each detector. The model parameters are: the location of the beam center, $\vec{r}$; the overall amplitude ("gain"), g; the beam width, σ; and the ellipticity in "plus" and "cross" orientations, p and c. The average beam width for BICEP2 is $\sigma = 0.221\,\mathrm{deg} \pm 0.006\,\mathrm{deg}$. Table **??** summarizes the measured beam parameters. Because they directly correspond to potential spurious polarization sources, we calculate the "differential" beam parameters for the two detectors in each pixel. Each of these differential parameters corresponds to a mismatch of the orthogonally polarized beams whose difference we use to measure the polarization of the CMB. For one of these effects, differential ellipticity, we use the measured parameters to subtract the effect in analysis. For differential gain and differential pointing, we "deproject" the effects, an operation that removes them without precise knowledge of their amplitude.[8–10] We use the beam maps (not the elliptical Gaussian model) as inputs to simulations that measure the residual spurious polarization after the subtraction and deprojection operations and the the residual contamination to be equivalent to $r \lesssim 0.001$.

2.2 Keck Main Beam Characterization

We use a similar proceedure to measure the *Keck Array* far-field beams. We use the same thermal source but mount it on a different mast so that the source–telescope distance remains 211 m. As for BICEP2, we fit the elliptical Gaussian model to the resulting maps. Table **??** also lists beam parameters for *Keck Array*. Differential pointing is significantly smaller in *Keck Array* than in BICEP2. Improvements in the detector design and fabrication process are responsible for this improvement.[11] Simulations of the potential impact of beam mismatch in *Keck Array* are in progress.

2.3 Far Side Lobe Characterization

We pay special attention to far side lobes of the beam, which we consider to be the part of the beam pattern that could potentially pickup the Galaxy or ground ($\gtrsim 15$ deg from the main beam). We use a two-stage mitigation strategy consisting of an absorbing, comoving forebaffle and a fixed, reflecting ground shield to limit the effects of the far side lobes intrinsic to the telescope. We measure the effectiveness of this strategy by removing the forebaffles and measuring the side lobes with an amplified noise source.

We measure the total power in far side lobes by comparing the beams with and without the forebaffle installed. When the forebaffle is installed, the detector optical loading increases by 3–6 $\mathrm{K_{CMB}}$for BICEP2. The forebaffle loading is higher for *Keck Array* (5–10 $\mathrm{K_{CMB}}$). Both have a pattern of higher loading for pixels near the center of the focal plane. Furthermore, this loading is higher than in BICEP1[12] ($< 2\,\mathrm{K_{CMB}}$). We found that the major source of additional forebaffle loading in *Keck Array* was shallow-incidence reflections off the inner (4-K) wall of the telescope. Based on this finding, we improved the blackening of the telescope wall for *Keck Array* 2014 observations (Section 3.2). After that improvement, the forebaffle loading was 2–4 $\mathrm{K_{CMB}}$.

To measure the spatial pattern of the far side lobes we use a modified beam mapping procedure. We create an amplified noise source from the Johnson noise of a $50\,\Omega$ resistor. A series of amplifiers, frequency multipliers, and filters brings the output to a broadband frequency range of $140 \sim 160$ GHz. For *Keck Array* we use an additional noise source with a band near 100 GHz (Figure 4). The source is linearly polarized, allowing measurement of side-lobe polarization. We mount the sources on a mast near BICEP2 (10 m away) or *Keck Array* (20 m away). We scan the telescope to achieve nearly full coverage up to 90 deg from the main beam. We repeat such observations with various source polarizations and attenuations and with the forebaffles on and off. Combining data from different source attenuations we make maps with ~ 70 dB dynamic range. In BICEP2 we find no sharp features in the far side lobes; however, we detect some diffuse power far from the main beam. With the forebaffle on, the region 25deg from the main beam contains $\lesssim 0.1\%$ of the total integrated power. By comparing maps made with and without the forebaffle, we calculate that the average fraction of power intercepted by the forebaffle is 0.7%. This corresponds to $3\,\mathrm{K_{CMB}}$, consistent with the increase in detector loading discussed above.

3. KECK ARRAY UPGRADES

We have the opportunity to upgrade the configuration of *Keck Array* every year. For the 2013 observing season, we replaced some detectors to improve their sensitivity. For the 2014 observing season, we made two main upgrades: first, we reduced the forebaffle loading based on the results of the measurements described in Section 2.3; second, we replaced two 150-GHz receivers with new 100-GHz receivers. Multi-frequency coverage is essential in light of the B-mode detection by BICEP2.

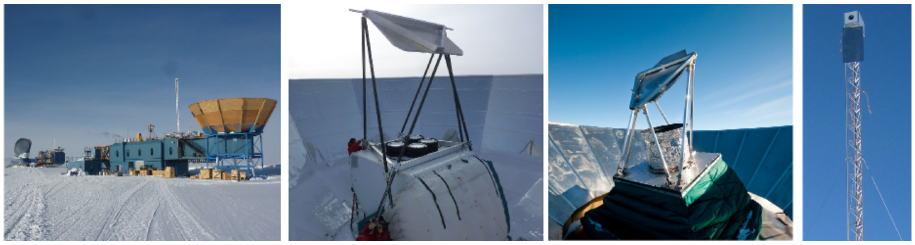

Figure 1. To make far-field beam maps we put microwave sources on masts and use flat mirrors to redirect the radiation into our telescopes. *Left:* The Dark Sector Laboratory (background) and Martin A. Pomerantz Observatory (foreground), housing BICEP2 and *Keck Array*, respectively. Each building has a mast for far-field beam mapping, and the distance from source to telescope is 211 m. *Center Left:* The flat mirror installed above *Keck Array*. *Center Right:* The flat mirror installed above BICEP2. *Right:* We enclose the microwave source on top of the mast in an absorptive box so that only radiation emitted from the intended aperture reaches the telescope.

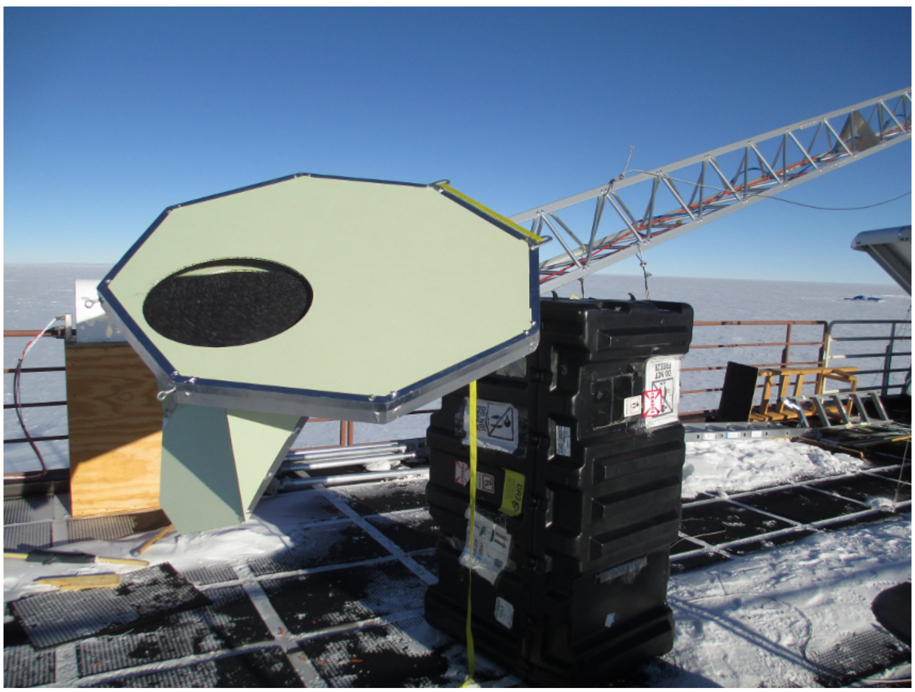

Figure 2. We characterized the main beams of BICEP2 and *Keck Array* using a chopped thermal source. Rotating blades alternately present sky ($\sim 15\,\mathrm{K}$) and ambient-temperature ($\sim 250\,\mathrm{K}$) radiation to the telescope. A flat mirror behind the chopper blades redirects sky radiation from zenith. The large active source aperture (20-cm diameter) provides high signal-to-noise.

3.1 Sensitivity Improvements

In preparation for the 2013 observing season, we replaced detectors measured to have sub-optimal sensitivity. We replaced all the detectors from the two receivers with the worst sensitivity in the 2012 season. The replacement detectors were the BICEP2 focal plane, known to have a noise equivalent temperature (NET, in CMB temperature units) of $15.8\,\mu\mathrm{K}\sqrt{\mathrm{s}}$, and a newly fabricated focal plane, measured to have high optical efficiency in the lab (40–50%). Finally, we replaced one tile (i.e. 25% of the detectors) in a third receiver because that tile had unusual, non-Gaussian noise properties in 2012 data. The combined NET for all *Keck Array* receivers in 2012 was $11.5\,\mu\mathrm{K}\sqrt{\mathrm{s}}$, calculated using the same method as in BICEP2.[13] Because of the detector replacements, the 2013 NET improved to $9.5\,\mu\mathrm{K}\sqrt{\mathrm{s}}$.

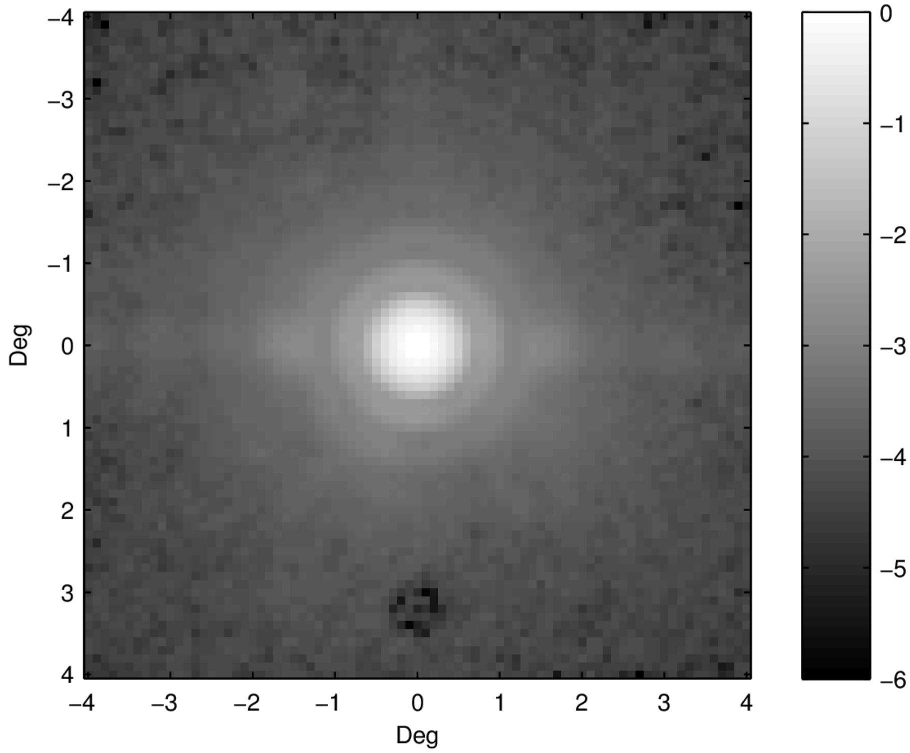

Figure 3. We combine the beam maps from all functional BICEP2 detectors to make an average beam map. The color scale is logarithmic. The main beam shape and Airy ring structure are consistent with simulations of the optics. Ghost beams are primarily due to cross talk in the readout system.

3.2 Reduction of Forebaffle Loading

We found that forebaffle thermal emission was contributing an unnecessarily high 5–10 $K_{CMB}$to the detector loading (Sec 2.3). Based on on-site and in-lab measurements, we identified the cause as shallow-incidence reflections off the inner (4-K) wall of the telescope. We blackened the telescope walls of both BICEP2 and *Keck Array* with carbon-loaded Stycast 2850 FT epoxy applied to Eccosorb HR-10 microwave absorber. However, we roughened the surface texture of the HR-10 for BICEP2, but did not do so for *Keck Array*. Based on lab measurements, the reflectance at shallow incidence angles (15–20deg) was up to ~ 5 times higher for the non-roughened surface used in *Keck Array*. We concluded that the additional forebaffle loading in *Keck Array* was due to emission from the forebaffle reflecting off the telescope walls and onto the detectors.

To reduce this forebaffle loading, we upgraded the *Keck Array* telescopes with "baffles," blackened rings placed to intercept shallow-incidence reflections. The baffles are thin aluminum annuli oriented perpendicular to the telescope walls so that any rays at shallow incidence to the walls will be at near-normal incidence to the baffles (Figure 5). We covered the baffles with the same absorber and epoxy mixture used on the walls. Each telescope has six baffles, evenly spaced between the two lenses. We set the baffle inner diameters so they would not intercept the detector main beams. The baffles are heat sunk to the 4-K telescope walls, and we expect negligible increase in loading due to emission from the baffles. We installed these baffles on all *Keck Array* receivers in preparation for the 2014 season. Based on the measured loading reduction, we expect a $5 \sim 10\%$ improvement in NET due to the installation of the baffles.

3.3 Addition of 100-GHz Receivers

For the 2014 season, we changed the observing band of two receivers from 150 GHz to 100 GHz. This change required replacement of the focal planes, lenses, and optical filters. The 100-GHz focal planes each have 144

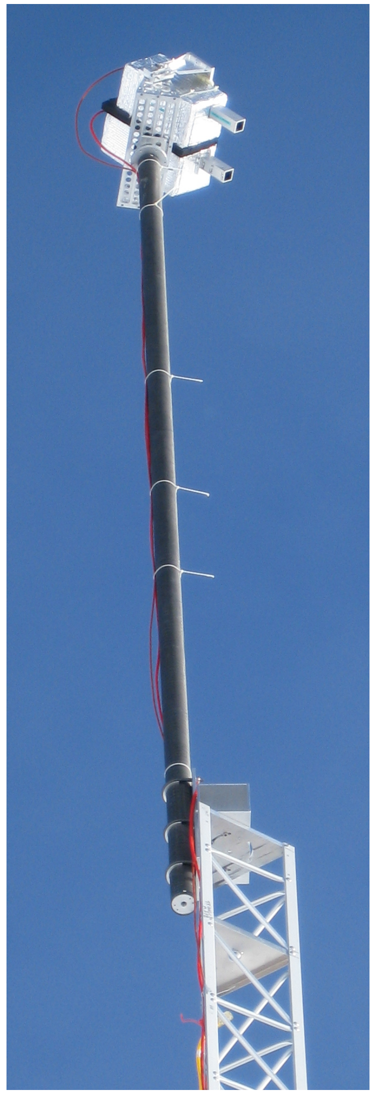

Figure 4. We use amplified noise sources to measure the spatial pattern of the far side lobes. Shown here is the source setup for *Keck Array*. To simultaneously map the 150-GHz and 100-GHz receivers, we mount two sources on the same mast, one tuned for each frequency band.

dual-polarization pixels (288 bolometers). The decrease compared to 150 GHz is due to scaling the design to the larger wavelength; a smaller number of pixels fits in the same focal plane area. We also used the same lens and filter design as 150 GHz. We changed the anti-reflection coating layer thicknesses to optimize for the new frequency band, and we used lower-cutoff ($4\,\mathrm{cm}^{-1}$, 120 GHz) metal mesh low-pass filters[14] to eliminate response to submillimeter radiation. Based on on-site Fourier transform spectroscopy (FTS) measurements, the typical center frequency and bandpass are **????**[?]

Keck Array 2014 CMB science observations began in March, and the 100-GHz receivers are performing well. Their combined NET is $17.4\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. Even with only ~ 3 months of data, the map depth from *Keck Array* at 100 GHz is already better than from three years of BICEP1. **Quantify map depth????** Analysis of these data is in progress.

Figure 5. In order to reduce detector loading from the warm forebaffles, we added baffles inside the cold telescope tubes of *Keck Array* for the 2014 season. *Left:* Shallow-incidence reflections off the telescope walls created an unintended coupling between the forebaffles and the detectors. *Right:* The baffles are oriented so that any such shallow-incidence rays will be at near-normal incidence on the baffles and therefore absorbed efficiently.

4. CONCLUSIONS

These proceedings have summarized improved beam characterization for BICEP2 and *Keck Array* and continued upgrades of *Keck Array*. The BICEP1 telescope beams have been measured at high signal-to-noise. As a result, the residual uncertainty in the BICEP2 B-mode detection from beam-related systematic effects was equivalent to $r \lesssim 0.001$. Measurements of far side lobes revealed an opportunity to reduce the detector optical loading in *Keck Array*; we upgraded the telescopes with internal cold baffles and confirmed the loading reduction. In 2013, after detector upgrades, the *Keck Array*sensitivity at 150 GHz was $9.5\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. In 2014, we installed two 100-GHz receivers with a combined sensitivity of $17.4\,\mu\mathrm{K}\sqrt{\mathrm{s}}$. Furthermore, in late 2014 we will deploy BICEP3, a 100-GHz telescope with 1280 dual-polarization pixels.[?] The resulting data will greatly improve our ability to distinguish CMB B-modes from foregrounds.

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Acknowledgments

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