Water Silhouettes against the Cosmic Microwave Background from the Most Distant Starburst Galaxies

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Abstract. Astrophysical objects can imprint distortions on the observed Cosmic Microwave Background (CMB) that give access to information for cosmology research that cannot be obtained otherwise. ΛCDM cosmology implies a linear scaling of the CMB temperature (T_CMB) with redshift z, but departures of this linear scaling behavior are allowed in more complex, but currently poorly observationally constrained cosmological models, such as those that include an evolution of physical constants, decaying dark energy, or axion-photon-like coupling processes. We here introduce a new method to directly measure T_CMB out to z > 6 based on H_2O absorption against the CMB, and describe our findings based on an initial detection towards the massive dusty starburst galaxy HFLS3 at z=6.34. This far exceeds the redshift range where direct T_CMB measurements across cosmic time have been previously possible, providing a crucial test of standard cosmology.

1 Introduction

The Cosmic Microwave Background (CMB) is the perhaps most important observable in cosmological studies, and it provides one of the key pieces of evidence for the Hot Big Bang model. Since the CMB acts as a background to all astrophysical objects we observe in the universe, different classes of objects can imprint different kinds of distortions onto the CMB, as the CMB photons travel on their path to Earth. The most common distortions at the wavelengths where the CMB is strongest are due to thermal emission from dust from our own Milky Way all the way to the first galaxies that form within the first billion years after the Big Bang, as well as non-thermal radio synchrotron emission in particular from active galactic nuclei.[7] Such signals locally enhance the observed radiation intensity, and need to be

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accounted for when studying the CMB. On the other hand, there also are processes that lead to a local reduction in the radiation intensity, leading to an absorption signal at certain wavelengths. The most well-known of these processes is the Sunyaev-Zel’dovich (SZ) effect observed toward massive galaxy clusters, which is dominated by a thermal component (and smaller kinetic component due to bulk cluster motion and relativistic corrections).[8, 12] The SZ effect occurs due to the fact that the intra-cluster medium in massive galaxy clusters consists of a hot plasma, which contains significant numbers of high-energy electrons. A fraction of CMB photons crossing the galaxy cluster potential thus are subject to Thomson scattering off the fast electrons, which increases their energy. Thus, at the position of the galaxy cluster, we observe a deficit in photons at wavelengths longward of 1.4 mm (i.e., an absorption signal), and a surplus at shorter wavelengths (i.e., an emission signal). Since the strength of the effect for a galaxy cluster of a given mass depends on the energy of the CMB photons (but not its distance, or redshift), and hence, the CMB temperature ($T_{\text{CMB}}$), observations of the SZ effect can be used as a cosmological probe, in particular to constrain $T_{\text{CMB}}$ as a function of redshift $z$. To date, this has been done successfully out to a redshift of $z \sim 1$, but too few sufficiently massive galaxy clusters are known at higher redshift to obtain reliable measurements to date.[2, 3]

In the next sections, we present a new cosmological tool to constrain $T_{\text{CMB}}$ out to $z > 6$, i.e., extending the range to >13 billion years of cosmic history (for more details, see [10]). However, a key question to ask is what makes such measurements scientifically interesting. In standard $\Lambda$CDM cosmologies, $T_{\text{CMB}}$ simply linearly increases as $(1+z)$, i.e., $T_{\text{CMB}}(z)=T_{\text{CMB}}(z=0)(1+z)$. However, this scaling behavior actually depends on a number of assumptions on the underlying physical laws and processes, some of which are not tested thoroughly on cosmological time and distance scales. For example, the dark energy density in standard models is assumed to be constant with time, but given our limited knowledge about the nature of dark energy, it remains entirely possible that it, for example, could decay over time.[5] This would introduce a scaling of $\Lambda$ with redshift, which could then also impact the $T_{\text{CMB}}$ evolution with $z$. Other possibilities to alter the standard $(1+z)$ scaling behavior include an evolution of physical constants with time,[13] or axion-photon-like coupling processes.[4] As such, investigations of the $T_{\text{CMB}}(z)$ scaling behavior implicitly constrain potential deviations from the standard cosmology. For simplicity, such deviations will be expressed in the following as deviations from the power law index of 1 in the $(1+z)^4$ term. The results in this work were first published by [10].

## 2 Water absorption against the CMB: Discovery

In the summer of 2020, we have used the IRAM NOEMA interferometer to spectrally scan the 3 mm window, targeting the $z=6.34$ massive dusty starburst galaxy HFLS3. In 2013, this galaxy was reported to be the most distant such object at the time based on the detection of CO $J=6\rightarrow5$ and $7\rightarrow6$, [CI] $2\rightarrow1$, and para-H$_2$O $2_{11}\rightarrow2_{02}$ emission, redshifted to 3 mm, in a 77 hr-long spectral scan with the CARMA interferometer.[9] Given the heterogeneous depth and limited sensitivity of the scan by today’s standards, and the substantial upgrade to NOEMA in the meantime, we decided to re-visit this system to more comprehensively characterize the molecular complexity in this early massive galaxy, observed only 880 million years after the Big Bang. Figure 1 shows a comparison of the previous to the new data, demonstrating the dramatic improvement in data quality, and the richness of the broad-band spectrum.[10] For the remainder of this article, we focus on a single line, redshifted to 75.9 GHz, or 3.95 mm. This line corresponds to the ortho-H$_2$O $1_{01}\rightarrow1_{01}$ transition at rest-frame 538 $\mu$m, and is seen in absorption (Fig. 2). The absorption is about twice as strong as the galaxy’s dust continuum emission, which suggests that it absorbs into the CMB at the redshift of HFLS3.
3 Water absorption against the CMB: Mechanism

To understand the nature of this line absorption signal into the CMB, we need to take into account the properties of the CMB and starburst, as well as the structure of the ortho-H$_2$O rotational line ladder. First, the expected $T_{\text{CMB}}$ at the redshift of HFLS3 is 20.0 K. Since the CMB acts as a background to the galaxy, a measurement of zero flux in the line would correspond to a line brightness temperature of 20 K, in equilibrium with the CMB. Second, the CMB can act as a heating source to the H$_2$O-bearing material, and excite the H$_2$O rotational ladder. The energy difference of the $1_{01}\rightarrow1_{01}$ transition is only $\Delta E/k_B=26.7$ K, where $k_B$ is the Boltzmann constant. Given the Boltzmann distribution of CMB photons, this means that a 20 K CMB can substantially excite the H$_2$O rotational ladder. RADEX[14] calculations suggest that, in such a configuration, 77.2% of the molecules will be in the ground $1_{01}$ state, while 20.3% will be in the first excited $1_{10}$ state. This level of excitation will bring the transition line in thermal equilibrium with the CMB. As a result, no net flux would be observed in any of the H$_2$O transitions.

However, the situation changes when accounting for the infrared radiation field contributed by the dust emission in the starburst HFLS3 itself. The dust in this galaxy has a temperature of $T_{\text{dust}}=63$ K, which acts as a background to the cold H$_2$O associated with HFLS3 (hence, causing absorption into the dust continuum), while at the same time carrying enough energy to also excite the H$_2$O rotational ladder. RADEX calculations suggest that, with the addition of the starburst radiation field, 68.0% of the molecules will be in the ground $1_{01}$ state, while only 14.6% will be in the first excited $1_{10}$ state. This excitation level corresponds to an excitation temperature of only $T_{\text{ex}}=17.4$ K, i.e., 2.6 K below the CMB temperature – explaining the absorption into the CMB. To understand this effect, it is necessary to consider the next higher transition of ortho-H$_2$O, i.e., $2_{21}\rightarrow1_{10}$. This transition occurs at $108\,\mu$m, i.e., substantially closer to the peak of the dust spectral energy distribution (SED) of HFLS3 of 73 $\mu$m than the $1_{10}\rightarrow1_{01}$ transition. This is important, because the starburst SED does not have a black-body shape, but a greybody shape, since the dust optical depth at shorter wavelengths on the Rayleigh-Jeans tail is significantly higher than at longer wavelengths. As a result, more $108\,\mu$m photons are available from the starburst to excite the $2_{21}\rightarrow1_{10}$ transition than $538\,\mu$m photons to excite the $1_{10}\rightarrow1_{01}$ transition. Under different circumstances, this would cause a bottleneck in the excitation of the $2_{21}\rightarrow1_{10}$ transition due to availability of molecules in the lower state. However, due to the availability of “additional” molecules excited by the CMB, the observed deficiency of molecules in the $1_{10}$ state compared to thermal excitation can occur.

4 How to measure $T_{\text{CMB}}(z)$ from water absorption

To explain the mechanism in the previous section, we have assumed that $T_{\text{CMB}}(z)$ is as predicted by standard cosmology. We now explain how the measurement can be used to test this assumption. Considering $T_{\text{CMB}}(z=6.34)$ at the distance of HFLS3 as the unknown, we need to know the dust SED shape of HFLS3, which is constrained well from observations, to determine the availability of 538 and $108\,\mu$m photons. We also need to know the column density of H$_2$O molecules to predict the depth of the absorption. Lastly, to obtain a line flux, we need to know the size of the absorbing region (i.e., the observed size of the dust continuum of HFLS3), and the filling factor of the absorbing clouds in the corresponding surface area. RADEX models with these inputs suggest that the data is consistent with $T_{\text{CMB}}(z=6.34)=16.4–30.2$ K (1$\sigma$ range), i.e., compatible with the 20.0 K expected in standard cosmology (Fig. 3). The models also suggest a minimal filling factor of almost 60%, which implies that the cold H$_2$O screen in front of the dust continuum is not highly clumpy, but
rather smooth. Given the implied gas masses, they also suggest that it is unlikely that the gas densities are high enough to significantly collisionally excite H$_2$O.[10]

In any case, the models also indicate that any significant contribution due to collisional excitation would weaken the effect, and thus, place more stringent constraints on the radiative excitation calculations considered here. Furthermore, they suggest that, for galaxies with dust SED shapes similar to HFLS3, the effect should only become observable at z~4.5, but that where observable, the line flux should be nearly independent of redshift out to at least z~12.

5 Conclusions

Our initial discovery of H$_2$O absorption against the CMB toward the massive dusty starburst galaxy HFLS3 is consistent with a CMB temperature at z=6.34 as expected in standard cosmology, and thus, with a non-evolving dark energy density with time.[10] Our models suggest that it should be possible to observe this effect rather commonly toward massive dust starburst galaxies at z>4.5, where the exact redshift cutoff depends on how similar the dust SED shapes of this population are to each other. Preliminary findings from an ongoing NOEMA follow-up campaign of this intial result appear to confirm these model predictions, which will be reported in future work.

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Figure 1. Observed-frame 3 mm spectrum of the starburst galaxy HFLS3 at \( z = 6.3369 \). Top: Comparison of the original CARMA “discovery” spectrum (gray histogram) and the new, more sensitive NOEMA spectrum (black/yellow histogram), demonstrating the major improvements possible with the greatly improved bandwidth and sensitivity of the upgraded array. The brightest lines are labeled. Bottom: NOEMA spectrum only, with additional lines labeled. The focus of this manuscript is the redshifted H\(_2\)O \( 1_{00} \rightarrow 1_{01} \) transition highlighted by the dashed red box, which absorbs through the galaxy’s dust continuum into the CMB (see Fig. 2 for additional details).
Figure 2. Zoom-in to the redshifted H$_2$O $1_{10} \rightarrow 1_{01}$ transition toward HFLS3 (left), and moment maps (right).[10] Left: Line spectrum at 40 MHz (158 km s$^{-1}$) resolution (blue), on top of the dust continuum of HFLS3 (yellow) and the CMB (gray; same labeling as Fig. 1). The black curve shows a fit to the line emission, and the dashed red curve shows the best-fit radiative transfer model. Right: Dust continuum at the wavelength of the line (538 $\mu$m rest frame; green contours), absorption before subtraction of the galaxy’s dust continuum, and after continuum subtraction (blue dashed contours; left to right). All maps are overlaid on an intensity scale map of the rest-frame 158 $\mu$m dust continuum observed with NOEMA at high spatial resolution.[9] The beam sizes are indicated at the bottom of the first panel. Continuum contours are shown in steps of 1$\sigma$, starting at $\pm 3 \sigma$. Line contours are shown in steps of 1$\sigma$, starting at $\pm 2 \sigma$. Negative intensity contours are dashed, and in the case of the H$_2$O line, indicate absorption strength.

Figure 3. Measurements of $T_{\text{CMB}} (z)$.[10] Symbols at $0 < z \leq 1$ are based on the thermal SZ effect.[1–3, 11] Symbols at $1.8 < z < 3.3$ are indirect constraints based on UV absorption line measurements toward background quasars, where different symbols at the same redshift correspond to different predictions for the same systems based on different assumptions for excitation due to collisional excitation of the tracer.[6] The symbol at $z=6.34$ corresponds to HFLS3, with 1$\sigma$ (black) and 2$\sigma$ (gray) uncertainty ranges shown. The orange dashed curve and shaded region show the best fit and uncertainty to all data, which remain consistent with standard cosmology (i.e., a $(1+z)$ scaling behavior). The dotted lines indicate a $\pm 10\%$ deviation from a power-law index of 1 for reference.