Analysis of Cosmic Microwave Background Radiation in the Presence of Lorentz Violation*

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We examine the effects Lorentz violation on observations of cosmic microwave background radiation. In particular, we focus on changes in polarization caused by vacuum birefringence. We place stringent constraints on previously untested violations.

Today, Einstein’s special relativity is understood to be a consequence of the more fundamental principle of Lorentz invariance. All modern physical theories are explicitly Lorentz invariant. The prominent position of Lorentz symmetry at the foundations of known physics makes its verification essential. Furthermore, violations of Lorentz symmetry have been identified as a promising avenue for searches for new physics arising from a unified description of nature, such as strings and other attempts at quantized gravity [1, 2, 3]. Such violations are expected be exceedingly tiny, but a number of experiments have achieved the necessary sensitivity to probe relativity at interesting levels [4].

Among the most sensitive experiments are those that involve polarized light from sources at cosmological distances [5, 6, 7, 8, 9, 10, 11]. The Cosmic Microwave Background (CMB) marks the limit of the observable universe [12], and therefore provides an excellent opportunity for tests of Lorentz invariance. Here we consider the effects of relativity violations on the CMB and use it to place constraints on a wide class of unconventional effects.

A general theoretical framework known as the Standard-Model Extension (SME) has been developed to facilitate the study of Lorentz-symmetry violations [2]. The SME is constructed out of the usual Standard Model of particle physics, augmented by all reasonable additions that are consistent with experimental constraints. The SME provides the low-energy limit of any realistic theory and characterizes Lorentz violation independent of its origin. The SME provides the theoretical backing for tests involving atomic clocks [13], neutral mesons [14], spin-polarized materials [15], particle traps [16], muons [17], neutrinos [18], and photons.

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Photon tests include modern versions of the classic Michelson-Morley experiment [19] and searches for changes in polarization of light from distant sources [6, 7, 11]. The latter tests yield sensitivities comparable to the best tests in any sector of the SME.

Changes in polarization arise out of an effect known as “cosmic birefringence.” This occurs when certain forms of relativity violations cause light to propagate as the superposition of two waves that differ in velocity and polarization. The difference in velocity causes the net polarization of the composite wave to evolve as the light propagates in vacua. Searches for this change in light from sources at cosmological distances yield extreme sensitivity to violations of Lorentz symmetry due to the long propagation times over which the tiny effects can accumulate. CMB radiation was created around 13 billion years ago, and has propagated more or less unhindered since. It constitutes the oldest unscattered light available to observation and is therefore an ideal source for birefringence searches.

CMB radiation is released during the epoch of recombination, a period when the Universe has cooled to a temperature at which atoms can form [12]. At this time, the Universe suddenly became transparent, and photons were now free to travel great distances without scattering. The CMB thus provides a snapshot of the Universe during a early stage of its evolution, approximately 300,000 years after the big bang. Signatures of the conditions in the early Universe are imprinted in the photons at the surface of last scatter, and provide a powerful probe into early cosmology.

While the Universe was extremely homogeneous during recombination, tiny variations in the temperature of the CMB blackbody spectrum have been firmly established by a host of experiments [20, 21, 22]. These variations point to small inhomogeneities in temperature and density of the primordial plasma. These inhomogeneities give rise to the possibility of polarized scattering [23]. In a homogeneous universe, there are no preferred directions. Consequently, scattering always results in zero total polarization. The argument fails if there exists a gradient in the density of scattering particles. This results in preferential scattering directions that depend on the polarization of the incident photons. The effect is that light scattering in certain directions with respect to the inhomogeneities can have a net polarization. Furthermore, these should correlate in a predictable way with the variations in temperature.

The CMB is generally decomposed into temperature $T$ and two types of polarization, the so-called $E$ and $B$ types. The $E$ and $B$ modes characterize any pattern of linear polarization
coming from all points on the sky. In general, we may also have circular polarization, type $V$, but this is not produced during recombination according to conventional physics [23]. The breakdown into $E$ and $B$ is convenient since only the $E$ type is expected to be correlated with the variations in temperature. Numerous observations [24, 25, 26, 27, 28] have confirmed the existence of $E$ polarization in the CMB and a correlation with $T$.

Next we examine the effects of birefringence on polarization in the CMB. Working within the SME framework, we construct all possible Lorentz-violating additions to conventional electrodynamics that can cause birefringence. A more detailed discussion is provided in Ref. [11]. Here we summarize the basic results. The Lorentz-violating modifications to electrodynamics can be classified in a similar manner as CMB polarization, as types $E$, $B$, and $V$. The changes in polarization are governed by a set of coefficients for Lorentz violation, which we write as $k^{(d)_V}_{lm}$, $k^{(d)_E}_{lm}$, and $k^{(d)_B}_{lm}$ for the three types of violations. These coefficients completely characterize the effects that violations of relativity can have on the polarization of the CMB. Nonzero values of these coefficients lead to birefringence, which will cause the pattern of polarization on the sky to change during the time it takes CMB radiation to propagate to Earth.

Some generic effects arise from the various coefficients. For example, roughly speaking, the index $d = 3, 4, 5, \ldots$ characterizes the frequency dependence of the changes in polarization [29]. For all $d > 3$ coefficients, higher frequency means stronger birefringence and a bigger change in the polarization. Only the $d = 3$ case causes changes in polarization that are independent of frequency. There are several signatures of this frequency dependence that may be detectable in CMB experiments that could provide signals of Lorentz violation. For example, typically CMB observations are made over frequency bands, not single frequencies. If the frequency dependence is large, the difference in the polarization at different frequencies in the band may be great enough so that the measured polarization (the average over the frequency band) is effectively reduced due to a loss of coherence across the band.

The indices $l$ and $m$ arise from a (spherical-harmonic) multipole decomposition of the Lorentz violation [30]. The value of these indices tell us something about the directional dependence of the resulting birefringence. Higher values of $l$ and $m$ say that the changes to the CMB polarization are more dependent on the location on the sky from which the radiation originates. Only the $l = 0$ and $m = 0$ coefficients cause a uniform change in the polarization across the entire sky. This unconventional direction dependence also leads
to some signals for Lorentz violation that could be sought in CMB experiments, such as reductions in net measured polarization.

One key feature of birefringence is that it causes mixing of the $E$, $B$, and $V$ type polarizations. Several generic signals for Lorentz violation arise from these mixings. For example, the $k^{(d)}_{(V)lm}$ coefficients result in mixing between the $E$- and $B$-type polarizations. For the CMB, this can cause unconventional behavior, such as a correlation between $T$ and $B$. Recall that in the conventional case we expect there to be a connection between the $T$ and $E$ patterns on the sky since the mechanism generating them are linked. If birefringence causes the $E$ polarization to be converted to $B$ polarization as it propagates to Earth then a correlation between $T$ and $B$ might arise.

The $k^{(d)}_{(E)lm}$ and $k^{(d)}_{(B)lm}$ coefficients cause a mixing of $E$, $B$, and $V$ polarization. A possible signal of this type of mixing is the generation of significant $V$ modes, i.e., circular polarization. As discussed above, the physics which produces the net polarization in the CMB is expected to produce only linear polarization. Observations of a large $V$ component in the CMB may point to birefringence caused by this type of mixing.

The numerous types of violations and there resulting effects makes a comprehensive search for birefringence in the CMB impractical. Here we provide a limited systematic comparison to available data. In principle, we could incorporate all available polarization data, but the complicated frequency dependence makes an analysis of this type difficult. So, as a first step, we limit our search to the BOOMERANG experiment [28], whose data are particularly well suited for our purposes. They report polarization measurements for types $E$ and $B$ for a single narrow frequency band at about 145 GHz. This relatively high frequency implies a greater sensitivity to most Lorentz violating effects. While incorporating lower-frequency data, will decrease the size of the errors found below, it is not likely to significantly effect the overall sensitivity.

Figure 1 shows our comparison of the BOOMERANG measured polarization to what we would expect in the event of nonzero Lorentz violation. The shaded regions indicate the ranges of coefficients which are preferred by the data at the 68% and 95% confidence level. Here we consider only one nonzero coefficient at a time, although, in principle, any combination of coefficients may exist in nature.

As can be seen in Fig. 1, we find some general features. All of the coefficients that we tested against BOOMERANG data prefer nonzero values at the 68% level, but are consistent
FIG. 1: A sample of relative likelihood versus coefficients for Lorentz violation. Boxes indicate calculated points, and the curve is the smooth extrapolation of these points. The dark-gray indicates the estimated 68% confidence level, and the light-gray region shows the 95% level.

with zero at 95%. This implies that we have a positive signal for Lorentz violation at the one-standard-deviation level. Future tests will be required to determine the reliability of this signal. We can also use the 95% constraints to place more conservative bounds on the coefficients for Lorentz violation. Table I summarizes the bounds we obtain for the lowest values of $d$.

Some results for the $d = 3$ and $d = 4$ cases exist \cite{5, 6, 7, 8}. Our positive signal for the $d = 3$ coefficients are consistent with the signal found by Feng et al. in an analysis utilizing both BOOMERANG and WMAP \cite{8}. Our result also constitutes an improvement, by a factor of $\sim 2$, on previous bounds for $d = 3$ coefficients, which were obtained by from observations of distant radio galaxies \cite{5}. For most the $d = 3$ coefficients, our analysis constitutes the most sensitive tests to date.

The bounds on $d = 4$ coefficients are comparable to those obtained from observations of distant galaxies \cite{6}. The highest sensitivities are achieved by observations of gamma-ray bursts \cite{7}. While not as sensitive as this search, the CMB provides the first test utilizing non-point-like sources. The advantage of a global source like the CMB is that it can constrain a much larger region of coefficient space, providing a more robust limit.
TABLE I: Order of magnitude estimate of bounds on coefficients with index $d$ from BOOMERANG.

Observations of the CMB have already provided exceptional tests of early cosmology and the evolution of the Universe. As demonstrated above, the CMB is also a powerful probe into the nature of spacetime itself. Current data have the ability to investigate fundamental spacetime symmetries with extreme precision. We not only find that the CMB yields constraints that are comparable or surpass any previous test, but a hint of Lorentz violation exists in current CMB data. Forthcoming observations [31, 32] will certainly yield improved sensitivity and are likely to provide excellent tests of special relativity.

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