Testing new physics with polarized light: Cosmological birefringence

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Cosmological rotation of linear polarization (cosmic birefringence or cosmic polarization rotation) provides an excellent probe to study new physics. We derived stringent limits on selected extensions of the Standard Model looking at the cosmological rotation of linear polarization for several datasets (Cosmic Microwave Background, Radio Galaxies, Radio Sources, Crab Nebula and Gamma-ray Bursts) corresponding at different energies for the photons and different distances of the sources.

Keywords: Cosmology; alternative theories; birefringence.

1. Introduction

Astrophysical and cosmological observations provide the main compelling evidences for new physics beyond the Standard Model. Precision measurements of light polarization from distant sources can be a powerful probe of theories beyond the Standard Model predicting modifications in the photon dispersion relation.

Our paper is organized as follows. Section 2 provides a comparison of the different conventions used in the definition of the linear polarization angle α. In Sec. 3 we present the different datasets used: Cosmic Microwave Background (CMB), UV distant Radio Galaxies, Radio Sources and Crab Nebula. In Sec. 4, for each model considered, we combine these datasets[1] - extending the work of[2] for CMB only - by taking into account the peculiar energy and distance dependence. Finally, we summarize and conclude in Sec. 5.

In this work, we use natural units, $\hbar = c = 1$, and assume a cosmological model with *Planck* estimates of cosmological parameters[3] $H_0 = h \cdot 100$ km/s/Mpc $= 67.2$ km/s/Mpc, $\Omega_{\mathrm{M}} = 0.32$ and $\Omega_\Lambda = 0.68$. The amount of rotation of the polarization plane is denoted by α.

2. Polarization conventions

Before combining the different constraints for the linear polarization rotation angle we remember the existence of two polarization conventions.

The definition of the Stokes parameters Q and U depends on the coordinate system used. Two are the possible definitions:

- IAU/IEEE[a]: in each point of the sky sphere is defined a right-handed reference system with x axis points toward North, y points toward East,

[a]International Astronomical Union/Institute of Electrical and Electronics Engineers.

and z-axis points inward (toward the observer). Therefore looking toward the source the linear polarization angle increases counter-clockwise (see Fig. 1).[4]

- HEALPix[b]: in each point of the sky sphere is defined a right-handed reference system with x axis points toward South, y points toward East, and z-axis points outward (toward the source). Therefore looking toward the source the linear polarization angle increases clockwise (see Fig. 2).[5]

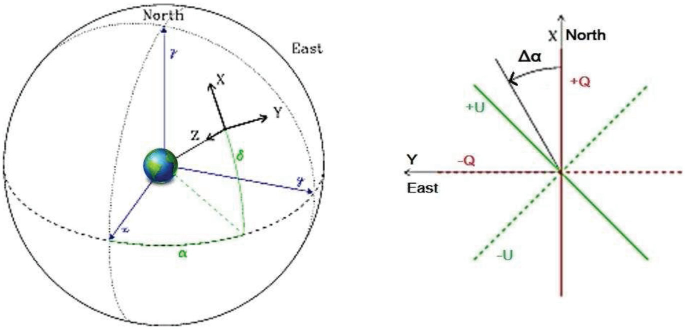

Fig. 1. (Left) A schematic illustration of IAU/IEEE coordinate conventions. (Right) The linear polarization angle increases counter-clockwise looking toward the source. See also[5,6].

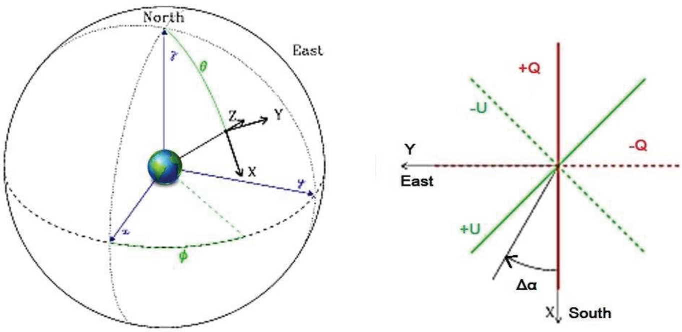

Fig. 2. (Left) A schematic illustration of HEALPix coordinate conventions. (Right) The linear polarization angle increases clockwise looking toward the source. See also[5,6].

Because different communities are involved in this kind of measurements attention is needed[6–8]. Since this review is mainly based on[1] we adopt the HEALPix conventions widely used for CMB observations.

[b]Hierarchical, Equal Area, and iso-Latitude Pixelisation of the sphere[5].

3. Dataset

We combine here several constraints on cosmological birefringence constraints over a very large energy (from few GHz to 10^9 GHz, from few μeV to hundreds of keV) and distance range (from z of few 10^{-7} to 1100). In order to clarify the specific contribution of each dataset we have decided to consider only a representative constraint for each single data set (see Table 1 for a summary)

Table 1. Current constraints on the cosmological birefringence angle α coming from a variety of astrophysical and cosmological observations; for each dataset we report the typical redshift and the effective energy.

Dataset	z	E [eV]	$\alpha \pm \Delta\alpha$ [deg]	Reference
CMB	1090	2.2×10^{-4}	-0.36 ± 1.9	[9]
UV Radio Galaxies	2.62	2.5	0.7 ± 2.1	[10]
Radio Sources	0.47	3.4×10^{-5}	1.6 ± 1.8	[11]
Crab Nebula	4.5×10^{-7}	2.3×10^{5}	1 ± 11	[12]

4. Analysis and results

In this section we constrain different models predicting birefringence, each one characterized by a different energy dependence.

4.1. *Energy-independent rotation*

Here, we will concentrate on an energy-independent birefringence effect linearly dependent on the propagation distance (Chern-Simons term[13], coupling between the electromagnetic field and a scalar (quintessential) field[14], ...). Taking into account the universe expansion the expected amount of rotation is:

$$\alpha(z_\star) = -\frac{1}{2} p_0 \int_0^{z_\star} \frac{1}{(1+z)H(z)} dz, \tag{1}$$

where $z_\star$ is the source redshift and p_0 is the time-component of a fixed time-like vector which is coupled to the electromagnetic field [c]. Combining all data excluding the GRB data point, as this is obtained assuming that the effect is energy-dependent, we obtain:

$$p_0 = (-0.93 \pm 2.9) \cdot 10^{-35} h \text{ eV}\,, \tag{2}$$

at 68% C.L. Note that the dominant contribution to the result comes from the CMB and UV Radio Galaxies, because of their significantly higher distance.

[c] In principle, as done in[13], one could consider a general vector p_α, but this would produce non-isotropic effects. Here we work under the assumption that birefringence is isotropic, so that only the time part of the vector could be present in the model.

4.2. *Energy-dependent rotation*

In this case our dataset (see Table 1) can be further extended. We rely not only on a direct measurement of the cosmological birefringence, but limits are derived also from linear polarization measurements at different energies.[15]

At high energies limits can be derived from polarization measurements of Gamma-ray bursts. We refer in particular as an example of the GRB capabilities to GRB061122[16], as this provides one of the latest results. The polarization direction is measured in two different energy bands, $250-350$ keV and $350-800$ keV, obtaining, respectively, $\phi_1 = 145 \pm 15$ and $\phi_2 = 160 \pm 20$ at 68% C.L. The distance of the GRB source is given as $z = 0.54$. As done in[16], we will use the conservative constraint on the rotation angle $\alpha = 0 \pm 50$ degrees (68% C.L.). [d]

At lower energies limits on the energy dependence of the linear polarization angle can be obtained looking at Mars polarized emission measured at different wavelengths.[17]

4.2.1. *Linear energy dependence*

This dependence can be due to the 'Weyl' interaction described in[18] and[19]. The polarization rotation angle depends linearly on the distance travelled by photons, $\Delta\ell$, and on the dimensionless scalar Ψ_0:

$$\alpha(E_0, z_\star) = 8\pi E_0 \Psi_0 \int_0^{z_\star} H(z)^{-1} dz \,, \tag{3}$$

where E_0 is the photon energy today. Combining the first four datasets of Table 1, the best-fit value for Ψ_0 is:

$$\Psi_0 = (3.0 \pm 9.1) \cdot 10^{-37} h \,, \tag{4}$$

at 68% C.L.; the dominant contribution comes from UV Radio Galaxies. This is an interesting example of a case in which the dominant contribution does not come from the highest energetic source (the Crab Nebula), that is what one might naively expect. In fact, the distance dependence plays an important role and can compensate for the lower energy of other more distant sources (see Fig. 3).

If we include also the constraint from GRB, this dominates and we obtain, at 68% C.L.: $\Psi_0 = (0.0 \pm 3.0) \cdot 10^{-40} h$. In both cases the constraint improves by several orders of magnitude the estimate based on CMB data only, $|\Psi_0| < 5.8 \cdot 10^{-33} h^2$.

4.2.2. *Quadratic energy dependence*

Quantum Gravity Planck-scale effects[20,21] can produce this kind of cosmological birefringence. Writing the coupling constant between the EM field and the vector

[d]Following[2] we introduce an effective energy depending on the functional dependence of α on energy and on the bandwidth of the different channels: $E = 530$ keV for the linear dependence and $E = 550$ keV in the quadratic case.

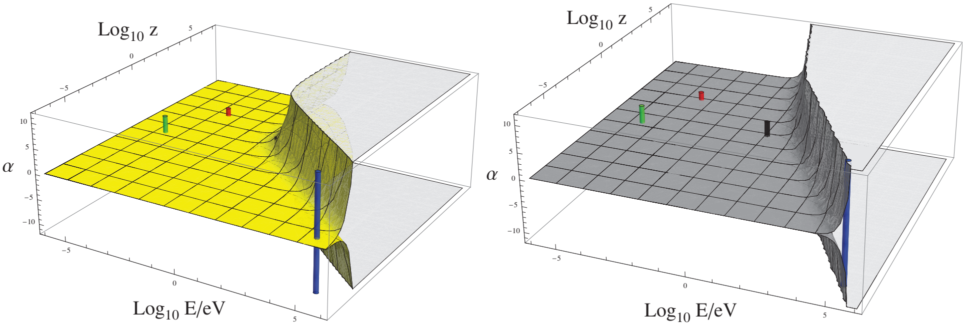

Fig. 3. Constraints for the cosmological birefringence angle α; black, green, red and blue points refer to UV Radio Galaxies, Radio Sources, CMB, Crab Nebula. (Left panel): for linear energy dependence the dominant contribution comes from UV Radio Galaxies, we show in yellow the value of $\alpha(E,z)$ fixed $\Psi_0 = (3.0 \pm 9.1) \cdot 10^{-37} h$. (Right panel): for quadratic energy dependence is Crab Nebula (highest energy source) that gives the most important contribution, we show in gray the value of $\alpha(E,z)$ fixed $\xi = (1.2 \pm 14.1) \cdot 10^{-11}$.

through a dimensionless parameter ξ and the Planck mass scale M_P, then:

$$\alpha(E_0, z_\star) = \frac{\xi}{M_P} E_0^2 \int_0^{z_\star} (1+z) H(z)^{-1} dz\,. \tag{5}$$

Using this formula for our analysis, the best-fit estimate for ξ is:

$$\xi = (1.2 \pm 14.1) \cdot 10^{-11}\,, \tag{6}$$

at 68% C.L. including all data points except GRB. Differently from what happened in the linear energy dependence, now it is actually the highest energy source (Crab Nebula) that gives the most important contribution, weighing the energy of the source more that its distance (see Fig. 3).

If we include also the constraint from GRB we obtain at 68% C.L.: $\xi = (0.0 \pm 8.6) \cdot 10^{-17}$. As expected, the GRB provides the dominant contribution and our result is indeed compatible with the upper limit presented in[16]. Again, in both cases the result improves the constraint, $\xi = (-0.22 \pm 0.22)$ at 68% C.L., based only on CMB dataset[2] by several orders of magnitude.

5. Conclusions

In the present work constraints on the rotation angle set by cosmological (CMB) and astrophysical (UV distant Radio Galaxies, Radio Sources, Crab Nebula, GRBs) observations were combined. Besides, updating current constraints on the models considered, this analysis provides also a useful guide for future polarization measurements aimed at investigating specific energy- and distance-dependent birefringence effects.

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