Polarization Rotation Over Cosmological Distances as a Probe to New Physics

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Recent studies in the rotation of the plane of polarization of electromagnetic waves over cosmological distances have opened up a new window to probe the structure of the universe. In what follows we discuss the possible origin of such a polarization rotation and the implications it would have on our present theories of cosmological structure.

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1. Introduction

Recent studies on synchroton radiation emitted by radio galaxies indicates that there is a systematic rotation of the plane of polarization that cannot be explained by Faraday rotation [1][2][3]. Though several authors have suggested that the polarization rotation might indicate a preferred axis of the universe or an intrinsic anisotropy of space time, there are several mechanisms originating from different fundamental modifications of conventional theory that can generate this polarization rotation. The importance of this effect lies in the fact that it can probe the fundamental structure of space time at very early times and over length scales commensurate with the size of the universe [4]. It can also probe theories of particle physics that are not testable in the terrestrial laboratory [5]. Polarization rotation implies that one helicity state travels at a rate different that the other helicity state, which implies a breakdown of parity invariance. It may or may not imply a breakdown of Lorentz invariance depending on the theory generating the polarization rotation. Actually, as early as 1982 Birch [6] observed the correlation of polarization angle with source location angle relative to a preferred axis in the universe. Kendall *et al.* [7] and Bietenholz *et al.* [8] later confirmed Birch's result which suggests that the universe had an intrinsic anisotropy associated with it. Whether this anisotropy is due to a fundamental breakdown of rotational symmetry or is due to the isometry of the cosmological frame that our universe chooses is an unanswered question. This latter fact suggests that the Goddel Universe[9] may be a physical reality and not just a mathematical curiosity. In what follows we discuss what modifications of fundamental physics can lead to a polarization rotation of electromagnetic radiation propagating over cosmological distances and what these modifications imply. Even if the present controversy over the correctness of data obtained for polarization rotation proves inconclusive the subject still carries with it a degree of ongoing importance. It is in this sense that this study should be taken, mainly as a guideline to try to uncover the source to any polarization rotation effects in the future.

2. Polarization Rotation in Modified Theories of Gravity and Particle Physics

The first modification of conventional electrodynamics that leads to cosmological birefringence is that due to the introduction of the axion field [10]. The axion is a pseudoscalar particle associated with a pseudoscalar field that is introduced into the Q.C.D. Lagrangian to insure that strong C.P. is not violated. For topological reasons [11] a term $\bar{a}\ F^{a}_{mu}\tilde{F}^{amu}$ should be present in the Q.C.D. Lagrangian where ($\bar{a}$) is a multiplicative constant. If however ($\bar{a}$) is promoted to a field through the breaking of the Pecci-Quinn symmetry (created to conserve strong C.P.) the pseudoscalar axion field ϕ then couples to the term $F^{a}_{mu}\tilde{F}^{amu}$. Through Q.C.D. instanton effects [12] the axion also couples to the E.M. pseudoscalar $e^{muab} F_{ab} F_{mu}$. If we start with

$$\bar{a} f e^{muab} F_{ab} F_{mu} \tag{2.1}$$

(here $\bar{a}$ = combination of fundamental constants), we find by adding a total derivative to Eq. (2.1) the following term appears in the Lagrangian

$$\bar{a} q e^{muab} F_{sb} F_{mu} \rightarrow 2\bar{a}\partial_{m} q e^{muab} A_{u} F_{ab} \tag{2.2}$$

Eq. (2.2) by itself when added to the Lagrangian of electromagnetism

$$�_{EM} = \frac{-1}{16p} F_{mu} F^{mu} \tag{2.3}$$

will rotate the plane of polarization of a plane polarized E.M. wave. If $¶_m q$ = constant four vector, the rotation is easy to calculate. This brings us to the second mechanism that leads to polarization rotation, Field *et al.* [13] motivated by the Chern-Simmons Lagrangian in (2+1) dimensions suggests that if a term

$$\frac{1}{4} P_m e^{muab} A_u F_{ab} \tag{2.4}$$

(P_m = constant for vector) is present in addition to Eq. (2.3). It will violate Lorentz invariance and parity but not gauge invariance. It will also rotate the plane of polarization of plane electromagnetic waves propagating over cosmological distances. If $P_m = (\vec{P}, m)$ = constant, a non-zero $\vec{P}$ implies that rotational symmetry of space is broken, if however $\vec{P} = 0$ and $m \neq 0$ then the theory would not be invariant to Lorentz boosts. At present there seems to be disagreement of whether or not cosmological polarization rotation has been found (Ref. 1) [14], but the very possibility of its presence suggests that we ask what modification of fundamental physics would cause it. The presence of the term of the form in Eq. (2.4) might also be related to the Adler , Bell, Jackiw anomaly [15] which could be responsible for the baryon asymmetry in the early universe and is a purely quantum effect. On a deeper level the presence of both Eq. (2.4) and the Adler, Bell, Jackiw anomaly might also be related to the modifications of continuous space time in the early universe that in a cosmetic sense generate Eq. (2.4) and the Adler, Bell, Jackiw anomaly.

In addition to the above modifications of fundamental physics that could be responsible for polarization rotation there is also the possibility that torsion could generate this effect. Torsion is the antisymmetric part of the affine connection ($T^a{}_{mu} = t^a{}_{mu} - t^a{}_{um}$) and represents an additional generalization to general relativity that has been pioneered by Heyl *et al.* [16]. The simplest torsion theory relates the cannonical energy momentum tensor the metric and the spin density to the torsion [17]. When torsion couples to electromagnetism there are two formulations studied in the past, the first modifies the conventional form of gauge invariance and leads to a theory in conflict with the equivalence principle [18][19]. The second formulation due to Gasparini *et al.* [20][21] retains the usual form of gauge invariance and introduces a pseudoscalar torsion potential that couples to electromagnetism through virtual fermion loops. This form of torsion is in harmony with the equivalence principle and leads to a modified theory of gravity with the following Lagrangian [22].

$$\mathcal{L} = \frac{C^4}{16p\,G}\left(R+\frac{3}{2}f_{,a}f^{,a}\right)\sqrt{-g} - \frac{1}{16p}F_{mu}F^{mu}\sqrt{-g} - \frac{a}{16p}\left(\frac{e^{muab}\,A_m F_{ua}\,f_{,b}}{\sqrt{-g}}\right.$$

(2.5)

here $R=$ curvature scalar, $f=$ pseudoscalar torsion potential, $F_{mn}=\frac{\partial A_m}{\partial x^u}-\frac{\partial A_u}{\partial x^m}=$ electromagnetic field tensor and $a=\frac{e^2}{\hbar c}$. The last term in Eq. (2.5) is identical to Eq. (2.4) if $f_{,a}=P_a$ is a constant vector. Eq. (2.5) had previously been shown to rotate the plane of polarization of E.M. waves even if $\phi_{,\alpha}$ is not a constant vector [23]. If $f_{,a}=P_a=$ constant it will rotate the plane of polarization just as Eq. (2.4) will and the two effects would be indistinguishable unless they are present simultaneously. Thus, any rotation in the plane of polarization would require other differentiating factors to distinguish between an axion interaction, pseudoscalar torsion or the presence of a constant vector P^m destroying Lorentz invariance and the isotropy of space time.

A fourth mechanism to rotate the plane of polarization for plane E.M. waves has been suggested by Ni [24]. Quite long ago Shiff [25] conjectured that any gravitational theory that obeys the WEP (weak equivalence principle) necessarily obeys the EEP (Einstein equivalence principle). The weak equivalence principle insures that all objects independent of composition accelerate at the same rate in a gravitational field. The EEP states that the result of all nongravitational experiments are the same in the gravitational field as in a uniformly accelerated frame. The EEP also insures that any gravitational field other than the metric must not couple directly to the matter field Lagrangian. Ni (Ref. 24) introduces a term

$$\frac{-f}{16p}\left(\frac{e^{muab}F_{ab}F_{mu}}{\sqrt{-g}}\right)\sqrt{-g} \tag{2.6}$$

into the Lagrangian of gravitation which violates the EEP but not the WEP. Here f = scalar gravitational field. Eq. (2.6) allows all uncharged particles to follow geodesics in a Riemanian metric, preserves electromagnetic gauge invariance and forbids the interaction of derivatives of f with $F_{\mu\nu}$. Eq. (2.6) leads to the rotation of the plane of polarization of plane EM waves and by itself cannot be distinguished from the other three mechanisms. Thus, any positive confirmation of Eq. (2.6) could lead to a violation of EEP and would encourage us to rethink the primitive basis for G.R.

Along with the above mechanisms that rotate the plane of polarization of E.M. waves traveling over cosmological distances we have polarization rotation due to quantum gravitational effects. Gambini and Pullen [26] have discussed how loop quantum gravity [27] introduces "parity violating weaves" in a polymer-like structure of space time [28]. These features of quantum gravity lead to a modification of Maxwell's equations due to the introduction of a fundamental unit of length (The Planck length), the modified Maxwell equations read

$$\begin{aligned}\frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla xE - 2x\ell_p\nabla^2 E\\ \frac{1}{c}\frac{\partial E}{\partial t} &= \nabla xB + 2x\ell_p\nabla^2 B\end{aligned} \tag{2.7}$$

In Eq. (2.7) x= constant close to 1, ℓ_p = Planck length. When Eq. (2.7) is applied to a plane electromagnetic wave propagating over cosmological distances it leads to a counterclockwise rotation proportional to $\frac{1}{l^2}$ [29]. Also since γ ray bursts are of cosmological origin (Ref. 1) their duration (10^{-1} sec) with structure appearing at widths of 10^{-3} sec can be used to set limits on the detectability of quantum induced dispersion between different helicity states. For bursts of E= 200kev, the difference between arrival time would be 10^{-5} sec according to Eq. (2.7). Thus a finer resolution of *g* ray bursts might very well be able to probe quantum gravity induced birefringence. Polarization rotation by "loop quantum gravity" proportional to $\frac{1}{l^2}$ (counter clockwise) should be contrasted with polarization due to Eq. (2.4) which is independent of λ (clockwise) and polarization rotation due to non-symmetric gravity [30] which is also independent of l (clockwise). In a historical paper Obukhov[31] has discussed "rotation in cosmology", in this paper he has pointed out that in a cosmology devoid of shear ($s_{mn} = 0$) rotation cannot be detected by parallax effects or the anisotropy of the cosmic microwave background radiation. He further emphasized that it can be detected by the angular dependence of standard cosmological tests (apparent magnitude *vs*. red shift) and the *N,Z* relation (which describes the number of sources observed in a given solid angle whose red shift is less than *Z*). Obukhov further points out that electromagnetic radiation propagating over cosmological distances will experience a rotation of the plane of polarization of the amount $f = wr\cos q + O(Z^2)$. Here

f = angle of polarization rotation,

r = distance from source to observer,

$$w = \text{rotation} = \left(\frac{1}{2} w_{mu} w^{mu}\right)^{-\frac{1}{2}}$$

w_{mn} = vorticity,

q = angle between r and axis of vorticity.

From data assembled by Birch (Ref. 6) we find the value of $w \cong (1.8 \times \pm .8) \times 10^{-18}$ sec^{-1}. Though this data is still the subject of controversy (for radio sources with $Z < .5$) it still suggests that a rotating cosmology can lead to polarization rotation in much the same way as other mechanisms discussed above. It is also understood that will all measurements Faraday rotation (which is rotation of the plane of polarization about a magnetic field along direction of propagation) has to be subtracted from the observed rotation to compare with the candidate theory in question.

If we consider the interaction of pseudoscalar torsion with two abelian gauge fields we can add additional terms to Eq. (2.5) that have identical form as the second and third terms of Eq. (2.5) but are described by a second field *Bm* and second coupling constant a_2. Such an additional abelian gauge field can correspond to a paraphoton[32], a long range field coupled to baryon number[33] or a mirror photon[34]. When the linearized equations of motion are studied we find that two dispersion relations result for right polarized light and two dispersion relations result for left polarized light. When the two left polarized waves combine with the two right polarized waves we find four polarization rotation angles, it turns out that two of these are identical yielding a total of three rotation angles (clockwise). One of the resulting signals will thus be twice as bright as the other two thus providing a signature to identify additional gauge fields coupled to pseudoscalar torsion. Thus the appearance of three distinct rotated polarized waves with one being twice as intense as the other two would be signal suggesting another abelian gauge field in nature coupled to pseudoscalar torsion. The magnitude of the rotation angles would serve to calculate the second coupling constant of the additional abelian gauge field coupled to psuedoscalar torsion.

In closing, the above possible sources of polarization rotation that include the axion (Ref. 10), explicit CPT violation (Ref. 13), pseudoscalar torsion (Ref. 22), violation of EEP (Ni's theory) (Ref. 24), quantum gravity (Ref. 26), non-symmetric gravity (Ref. 30) and cosmological rotation (Ref. 31) should be more thoroughly studied to analyze the distinguishing features of each with the hope of finding true modifications of fundamental physics. It is also hoped that data on polarization rotation will be reconsidered with the intent of discovering true rotation polarization rather than systematic fluctuations. Whatever the ultimate source may be of modifications to particle theory and cosmology the above possibilities hold a high priority in the list of possible alterations of fundamental physical theory that will be found in the future.

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