Physics Letters A 378 (2014) 3413–3418

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Dilaton field and cosmic wave propagation

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ARTICLE INFO

Article history:
Received 1 September 2014
Received in revised form 24 September 2014
Accepted 26 September 2014
Available online 2 October 2014
Communicated by P.R. Holland

Keywords:
Classical electrodynamics
Dilaton field
General Relativity
Equivalence principle
Axion field
Skewon field

ABSTRACT

We study the electromagnetic wave propagation in the joint dilaton field and axion field. Dilaton field induces amplification/attenuation in the propagation while axion field induces polarization rotation. The amplification/attenuation induced by dilaton is independent of the frequency (energy) and the polarization of electromagnetic waves (photons). From observations, the agreement with and the precise calibration of the cosmic microwave background (CMB) to blackbody radiation constrains the fractional change of dilaton $|\Delta\psi|/\psi$ to less than about 8×10^{-4} since the time of the last scattering surface of the CMB.

1. Introduction

The concept of metric in Minkowski's spacetime formulation [1] of special relativity together with the proposal of Einstein Equivalence Principle [2] facilitated the genesis of general relativity. While metric field is the basic dynamical entity of gravity in general relativity, Einstein Equivalence Principle (EEP) dictates the coupling of gravity to matter. In putting Maxwell equations into a form compatible with general relativity, Einstein noticed that the equations can be formulated in a form independent of the metric gravitational potential in 1916 [3,4] shortly after his completion of general relativity with further developments worked out by Weyl [5], Murnaghan [6], Kottler [7] and Cartan [8]. In this introduction, we first review the premetric formulation of electromagnetism and then address to the issue of construction of the core metric, the dilaton field and the axion field from the nonbirefringent wave propagation.

1.1. Premetric formulation of electromagnetism

Maxwell equations in terms of field strength F_{kl} ($\boldsymbol{E}, \boldsymbol{B}$) and excitation (density) H^{ij} ($\boldsymbol{D}, \boldsymbol{H}$) do not need metric as primitive concept. Field strength F_{kl} ($\boldsymbol{E}, \boldsymbol{B}$) and excitation H^{ij} ($\boldsymbol{D}, \boldsymbol{H}$) can all be independently operational defined (see, e.g., Hehl and Obukhov [9]). Maxwell equations of macroscopic/spacetime electrodynamics expressed in terms of these quantities are

$$H^{ij}{}_{,j} = -4\pi J^i, \tag{1a}$$

$$e^{ijkl} F_{jk,l} = 0, \tag{1b}$$

where J^k is the charge 4-current density and e^{ijkl} is the completely anti-symmetric tensor density with $e^{0123} = 1$ (see, e.g., Hehl and Obukhov [9]). We use units with the light velocity c equal to 1. To complete this set of equations, one needs the constitutive relation between the excitation and the field:

$$H^{ij} = (1/2)\chi^{ijkl} F_{kl}. \tag{2}$$

Both H^{ij} and F_{kl} are antisymmetric, hence χ^{ijkl} must be antisymmetric in i and j, and k and l. Therefore the constitutive tensor density χ^{ijkl} has 36 independent components. A general linear constitutive tensor density χ^{ijkl} in electrodynamics can be decomposed into principal part (P), axion part (Ax) and skewon part (Sk) [9]:

$$\chi^{ijkl} = {}^{(\mathrm{P})}\chi^{ijkl} + {}^{(\mathrm{Sk})}\chi^{ijkl} + {}^{(\mathrm{Ax})}\chi^{ijkl},$$
$$(\chi^{ijkl} = -\chi^{jikl} = -\chi^{ijlk}) \tag{3}$$

with

$${}^{(\mathrm{P})}\chi^{ijkl} = (1/6)\big[2(\chi^{ijkl} + \chi^{klij}) - (\chi^{iklj} + \chi^{ljik}) - (\chi^{iljk} + \chi^{jkil})\big], \tag{4a}$$

$${}^{(\mathrm{Ax})}\chi^{ijkl} = \chi^{[ijkl]} = \varphi e^{ijkl}, \tag{4b}$$

$${}^{(\mathrm{Sk})}\chi^{ijkl} = (1/2)(\chi^{ijkl} - \chi^{klij}). \tag{4c}$$

Decomposition (3) is unique. The principal part has 20 degrees of freedom. The axion part has one degree of freedom. The skewon

http://dx.doi.org/10.1016/j.physleta.2014.09.049

part has 15 degrees of freedom. The skewon field was proposed by Hehl, Obukhov and Rubilar [10,11] and has been studied extensively [12–19]. In a recent paper [17], we have studied the electromagnetic wave propagation and the observational constraint on the skewon field in the weak field limit. We found that the CMB spectrum measurement gives very stringent constraint on the Type I skewons. From the dispersion relation we show that no dissipation/no amplification condition implies that the additional skewon field must be of Type II. For Type I skewon field, the dissipation/amplification is proportional to the frequency and the CMB spectrum would deviate from Planck spectrum in shape. From the high precision agreement of the CMB spectrum to 2.755 K Planck spectrum, we constrain the Type I cosmic skewon field $|^{(\mathrm{SkI})}\chi^{ijkl}|$ to $\leq$ a few $\times 10^{-35}$.

In the skewonless case, the well-observed nonbirefringence condition in the astrophysical/cosmological propagation constrains the spacetime constitutive tensor density χ^{ijkl} to a core metric plus dilaton field and axion field very stringently.

The axion part of the constitutive tensor gives pseudoscalar-photon interaction [20]. This pseudoscalar–photon interaction has been studied in detail in [21,22]. It induces CPR (Cosmic Polarization Rotation). The astrophysical and cosmological constraints on CPR and, hence, on axion field are reviewed in [23–26]. In macroscopic electrodynamics, Hehl, Obukhov, Rivera and Schmid [27] have studied and clarified that the chromium sesquioxide Cr_2O_3 crystal is an axionic medium. Their paper has explicitly demonstrated that the four-dimensional pseudoscalar φ (4b) exists in macroscopic electrodynamics. In view of the existence of axionic material [27], searching for dilatonic material and skewonic material in macroscopic electrodynamics would also be interesting.

1.2. Derivation of spacetime structure from premetric electrodynamics

The issue here is that how to (with what conditions can we) reach a metric or, owing to conformal invariance, how to reach a Riemannian light cone (a core metric up to conformal invariance) from the constitutive tensor. This issue has been studied rather thoroughly in the skewonless case, i.e. in the case χ^{ijkl} is symmetric under the exchange of the index pairs ij and kl. In this case, the Maxwell equations can be derived from the Lagrangian density $L(= L_I^{(\mathrm{EM})} + L_I^{(\mathrm{EM\text{-}P})})$ with the electromagnetic field Lagrangian density $L_I^{(\mathrm{EM})}$ and the field–current interaction Lagrangian density $L_I^{(\mathrm{EM\text{-}P})}$ given by

$$L_I^{(\mathrm{EM})} = -\big(1/(8\pi)\big)H^{ij}F_{ij} = -\big(1/(16\pi)\big)\chi^{ijkl}F_{ij}F_{kl}, \tag{5}$$

$$L_I^{(\mathrm{EM\text{-}P})} = -A_k J^k, \tag{6}$$

where $\chi^{ijkl} = \chi^{klij} = -\chi^{jikl}$ is a tensor density of the gravitational fields or matter fields to be investigated, A_i the electromagnetic 4-potential, $F_{ij} \equiv A_{j,i} - A_{i,j}$ the electromagnetic field strength tensor and comma denoting partial derivation [20,28]. We note that only the part of χ^{ijkl} which is symmetric under the interchange of index pairs ij and kl contributes to the Lagrangian density, and hence, there is no skewon contribution.

One way to reach a core metric for spacetime constitutive tensor is through Galileo weak equivalence. In 1970s, we started from Galileo's Equivalence Principle and derived its consequences for an electromagnetic system whose Lagrangian density is $L_I^{(\mathrm{EM})} + L_I^{(\mathrm{EM\text{-}P})} + L_I^{(\mathrm{P})}$ where $L_I^{(\mathrm{EM})}$ and $L_I^{(\mathrm{EM\text{-}P})}$ are defined in (5) and (6) and the particle Lagrangian density $L_I^{(\mathrm{P})}$ defined as $-\sum_I m_I (ds_I)/(dt)\delta(\boldsymbol{x} - \boldsymbol{x}_I)$ with m_I the mass of the Ith (charged) particle and s_I its 4-line element from the metric g_{ij} [20,28]. The result is that the constitutive tensor density χ^{ijkl} can be constrained and expressed in metric form with additional pseudoscalar (axion) field φ:

$$\chi^{ijkl} = (-g)^{1/2}\big[(1/2)g^{ik}g^{jl} - (1/2)g^{il}g^{kj}\big] + \varphi e^{ijkl}, \tag{7}$$

where g^{ij} is the inverse of g_{ij} and $g = \det(g_{ij})$. Thus the particle metric g_{ij} induces the constitutive tensor density χ^{ijkl} and generates the light cone for electromagnetic wave propagation. We notice that the axion field does not contribute to the ray propagation in the lowest-order eikonal approximation [29–33].

However, there are two aspects of this derivation which are not quite satisfying. First, the constitutive tensor must match the particle metric in a certain way from the Galileo Equivalence Principle: the metric is not constructed directly from the constitutive tensor. This is not quite satisfying from the theoretical point of view. Second, the Galileo Equivalence Principle is only verified to high precision for unpolarized test bodies. The tests on polarized bodies which include polarized electromagnetic energy are not very precise. This is not quite satisfying from experimental point of view. Noticing that the pulses from pulsars propagating in the galactic gravitational field arrive at earth at the same time independent of polarization, i.e., are nonbirefringent, we began to use the nonbirefringence condition as a starting point in the later part of 1970s [29–31]. This would be satisfying in two aspects. First, the equal-time arrival of pulses independent of polarization can be formulated as a statement of Galileo Equivalence Principle for photons and is therefore theoretically satisfying. Second, the nonbirefringence is tested to high precision with pulses from pulsars and is therefore experimentally satisfying. From the non-birefringent propagation in spacetime to high precision, we constrain the constitutive tensor density to core metric form and construct the light cone of electromagnetic wave propagation with an additional scalar (dilaton) field ψ and an additional pseudoscalar (axion) field φ [29–31]. The theoretical condition for no birefringence (no splitting, no retardation) for electromagnetic wave propagation in all directions is that the constitutive tensor density χ^{ijkl} can be written in the following form

$$\chi^{ijkl} = (-h)^{1/2}\big[(1/2)h^{ik}h^{jl} - (1/2)h^{il}h^{kj}\big]\psi + \varphi e^{ijkl}, \tag{8}$$

where h^{ij} is a metric constructed from χ^{ijkl} ($h = \det(h_{ij})$ and h_{ij} the inverse of h^{ij}) which generates the light cone for electromagnetic wave propagation [29–32]. We constructed the relation (8) in the weak-violation/weak-field approximation of the Einstein Equivalence Principle (EEP) and applied to pulsar observations in 1981 [29–31]; Haugan and Kauffmann [32] reconstructed the relation (8) and applied to radio galaxy observations in 1995. After the cornerstone work of Lämmerzahl and Hehl [33], Favaro and Bergamin [34] finally proved the relation (8) without assuming weak-field approximation (see also Dahl [35]). Polarization measurements of electromagnetic waves from pulsars and cosmologically distant astrophysical sources yield stringent constraints agreeing with (8) down to 2×10^{-32} fractionally (for a review, see [25,26]).

The complete agreement with EEP for photon sector requires (i) no birefringence; (ii) no polarization rotation; (iii) no amplification/no attenuation in spacetime propagation. With no birefringence, any skewonless spacetime constitutive tensor must be of the form (8) as we just reviewed in the last paragraph. In the next section, we show that with the condition of no polarization rotation and the condition of no amplification/no attenuation satisfied, the axion φ and the dilaton ψ should be constant respectively. That is, no varying axion field and no varying dilaton field respectively; the EEP for photon sector is observed; the spacetime constitutive tensor is of metric-induced form only. Thus we tie the three observational conditions to EEP and to metric-induced spacetime constitutive tensor in the photon sector. This is aesthetic and more satisfying. Previously we have worked out the condition on polarization rotation for axion field [21,25,26]. In the next section, we work out the no amplification/no attenuation condition for dilaton field.