Cosmic optical activity in the spacetime of a scalar-tensor screwed cosmic string

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Measurements of radio emission from distant galaxies and quasars verify that the polarization vectors of these radiations are not randomly oriented as naturally expected. This peculiar phenomenon suggests that the spacetime intervening between the source and observer may be exhibiting some sort of optical activity, the origin of which is not known. In the present paper we provide a plausible explanation to this phenomenon by investigating the rôle played by a Chern-Simons-like term in the background of an ordinary or superconducting screwed cosmic string in a scalar-tensor gravity. We discuss the possibility that the excess in polarization of the light from radio-galaxies and quasars can be understood as if the electromagnetic waves emitted by these cosmic objects interact with a scalar-tensor screwed cosmic string through a Chern-Simons coupling. We use current astronomical data to constrain possible values for the coupling constant of this theory, and show that it turns out to be: \( \lambda \sim 10^{-26} \) eV, which is two orders of magnitude larger than in string-inspired theories.

I. INTRODUCTION

The Cosmological Principle postulates that the Universe is homogenous and isotropic on large scales. This means that there exists no preferred direction on the sky, and that in any patch of the sky we look into we may expect to find roughly the same distribution of matter and radiation. This premise was verified by the COBE satellite up to about \( 10^{-6} \) in temperature anisotropy in the cosmic microwave background radiation, a residual from the Big Bang. However, recent measurements of radio and optical emission from distant radio-galaxies and quasars provide clear evidence that the linearly polarized light emitted by these objects presents an additional rotation of its polarization plane, which remains even after Faraday rotation, the one produced by its interaction with the intergalactic plasma, is extracted. This may represent evidence for cosmological anisotropy on large scale.

In particular, Hutsemékers and Lamy found that the polarization vectors of light from quasars are not randomly oriented on the sky as standard understanding suggested. To confirm this effect they studied a sample of 170 optically polarized quasars with accurate polarization measurements. Their analysis showed that in some regions the polarization position angles appear concentrated around preferential directions, what suggests the existence of large-scale coherent orientations or alignments of the quasar’s radiation polarization vectors. In their measurements, the hypothesis of uniform distribution of polarization position angles may be rejected at the 1.8 % significance level. Though the sample seemed to be statistically not too much significant, further surveys confirm its unexpected nature. The occurrence of coherent orientations over cosmic distances, they claimed, seems to point towards the existence of new non-standard effects relevant to cosmology.

Other authors had claimed to find evidence for cosmological birefringence. This claim, initially contentious, was confirmed by subsequent studies that demonstrated the existence of such an effect up to a high confidence level. Thenceforth, these actual evidences give new motivations to investigate more detailed this possibility.

The implications of the possible existence of a preferred direction over cosmological distances have been discussed in the context of theories of gravitation and observational cosmology. Such a phenomenon, if it exists, would imply the violation of the Lorentz invariance, bringing unpredictable consequences for fundamental physics.

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The idea that the intergalactic space is a birefringent medium has been considered for a long time. Several potential sources of optical activity have already been studied. They include the scattering produced by atoms, by a neutrino sea, and also by a background Kalb-Ramond torsion (axion) field in the context of a heterotic string theory [1]. In particular, the scattering-inspired theories suggested that the intergalactic medium contains neutral atoms and microwave radiation immersed in a neutrino or antineutrino sea [5]. The sea is very hard to detect experimentally [4, 7] as a result of its low energy and its exclusively weak interactions. Electromagnetic radiation travelling through the intergalactic medium interact with its components, and if this radiation is initially plane polarized, the plane of polarization would rotate.

In this paper, instead of the idea of a neutrino or axion-like sea interacting with the electromagnetic radiation or the model inspired on heterotic strings, we will consider that a screwed cosmic string (SCS) on the background, whose gravitational effects are described by a scalar-tensor theory, has the same effect, i. e., the plane polarized electromagnetic radiation from high redshifts cosmic sources has the plane of polarization rotated when it is travelling through the spacetime generated by this screwed cosmic string. In the literature, the association of such anisotropy with a torsion background has been considered [18, 19, 20, 21].

On the other hand, the assumption that gravity may be intermediated by a scalar field (or, more generally, by many scalar fields) in addition to the usual symmetric rank-2 tensor of Einstein’s general relativity has considerably revived in recent years [22]. It has been argued that gravity may be described by a scalar-tensor gravitational field, at least at sufficiently high energy scales [23, 24, 25].

From the theoretical point of view, scalar-tensor theories of gravitation, in which the gravitational interaction is mediated by one or several long-range scalar fields in addition to the usual tensor field present in Einstein’s theory, are the most natural alternatives to general relativity. In these theories the gravitational interaction is mediated by a (spin-2) graviton and by a (spin-0) scalar field [26, 27]. If gravity is essentially a scalar-tensor theory, there will be direct implications for cosmology and experimental tests of the gravitational interaction [12, 22, 28]. In particular, any gravitational phenomena will be affected by the variation of the gravitational constant $G_0$. At sufficiently high energy scales where gravity becomes scalar-tensor in nature, it seems worthwhile to analyze the behaviour of matter and radiation fields in the presence of a scalar-tensor gravitational field, specially those generated during the early universe by objects such cosmic strings. In this context, some authors have studied solutions for cosmic strings and domain walls in Brans-Dicke [30], in dilaton theory [31] and in situations with more general scalar-tensor couplings [32].

The dilaton-torsion identification was previously made in a modified scalar-tensor theory, where the torsion field is generated by a scalar field [25]. Torsion is important from the phenomenological point of view and it may be relevant to cosmology. This importance is associated with the modifications of kinematic quantities like shear, vorticity, acceleration, expansion and their evolution equations derived in the presence of torsion [24, 25, 33, 34, 35].

A cosmic string [37] is a topological defect that may have been formed during phase transitions in the realm of the early Universe [38]. Its gravitational field, in the context of General Relativity is quite remarkable: a particle placed at rest around a straight, infinite, static cosmic string will not be attracted to it. The richness of new ideas this defect brought along with general relativity seems to justify the interest in the study of this structure, and specifically the role played by it in the framework of cosmology due to the fact that it carries a large energy density and for this reason it could be a potential source for primordial density perturbations [39].

In this paper we will consider the coupling of a Chern-Simons-like (CS) term with the spacetime of a screwed cosmic string, in a scalar-tensor gravity, to introduce a novel explanation of the observations suggesting an optical activity of spacetime. This optical activity manifests itself through the peculiar orientation of the polarization vectors of radio waves emitted by distant quasar and galaxies, which seems to indicate some kind of anisotropy over cosmological distances.

This paper is organized as follows: In Section II we introduce the physics of the scalar-tensor screwed cosmic string (SCS). In Section III, the dilatonic solution for the SCS is used as a background to study, in Section IV, the coupling of a gauge invariant Chern-Simons-like term. In Section V, we study the superconducting string case and a comparison is done with general relativity effects. In Section VI an overall discussion of our results is given. We stress the possibility of using this approach to explain the data evidencing the optical activity of the spacetime intervening between us and distant quasars and galaxies. Finally, in Section VII we provide some closing remarks.

II. SCREWED COSMIC STRING IN SCALAR-TENSOR GRAVITY

The scalar-tensor theory of gravity with torsion is an extension of Einstein’s General Relativity to which a scalar field is coupled minimally to the gravitational field and a dynamical torsion term is considered additionally. The action describing this coupling, here presented in the Jordan-Fierz frame, takes the form [25, 27]...
\[ I = \frac{1}{16\pi} \int d^4x \sqrt{-\tilde{g}} \left[ \tilde{\phi} \tilde{R} - \frac{\omega(\tilde{\phi})}{\tilde{\phi}} \partial_{\mu} \tilde{\phi} \partial^{\mu} \tilde{\phi} \right] + I_m(\tilde{g}_{\mu\nu}, \Psi) . \] (1)

where \( I_m(\tilde{g}_{\mu\nu}, \Psi) \) is the action of the matter, which in the general case takes into account all fields. Here we will consider the presence of spinor fields in the action. The function \( \omega \) in a general scalar-tensor theory has a \( \tilde{\phi} \) dependence, but in the specific case of the Brans-Dicke theory it is a constant. In this case the scalar curvature \( \tilde{R} \), appearing in Eq.(1) in the Jordan-Fierz frame, can be written as \[ \tilde{R} = \tilde{R}(\{\}) + \frac{\epsilon}{\tilde{\phi}^2} \partial_{\mu} \tilde{\phi} \partial^{\mu} \tilde{\phi} , \] (2)

where \( \tilde{R}(\{\}) \) is the Riemann scalar curvature in the Jordan-Fierz frame and \( \epsilon \) is the torsion coupling constant \[27\]. It is worth to stress that in the scalar curvature \( \tilde{R} \), the scalar function \( \tilde{\phi} \) (the dilaton field) can act as a source of the torsion field. Therefore, in the absence of string spin, the torsion field may be generated by the gradient of this scalar field \[24\]. In this case the torsion can be propagated with the scalar field, and can be written as

\[ S_{\lambda^\nu}^{\alpha} = (\delta_{\mu}^{\lambda} \partial_{\nu} \tilde{\phi} - \delta_{\nu}^{\lambda} \partial_{\mu} \tilde{\phi})/2\tilde{\phi} . \] (3)

The most general affine connection \( \Gamma_{\lambda^\nu}^{\alpha} \) in this theory receives a contribution from the contortion tensor \( K_{\lambda^\nu}^{\alpha} \) throughout the definition

\[ \Gamma_{\lambda^\nu}^{\alpha} = \{\tilde{\gamma}_\nu\} + K_{\lambda^\nu}^{\alpha} , \] (4)

where the quantity \( \{\tilde{\gamma}_\nu\} \) is the Christoffel symbol computed from the metric tensor \( \tilde{g}_{\mu\nu} \), whilst the contortion tensor \( K_{\lambda^\nu}^{\alpha} \) can be written in terms of the torsion field as

\[ K_{\lambda^\nu}^{\alpha} = -\frac{1}{2}(S_{\lambda^\nu}^{\alpha} + S_{\nu^\lambda}^{\alpha} - S_{\lambda^\nu}^{\alpha}) . \] (5)

Although the action proposed in Eq.(1) shows explicitly this scalar-tensor gravity feature, for technical reasons, we will adopt the Einstein (conformal) frame in which the kinematic terms of the scalar and tensor fields do not mix. In this frame the action is given as

\[ I = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left[ R - 2g^{\mu\nu} \partial_{\mu} \phi \partial_{\nu} \phi \right] + I_m[\Psi_m, \Omega^2(\phi)g_{\mu\nu}] , \] (6)

where \( g_{\mu\nu} \) is a pure rank-2 tensor in the Einstein frame, and \( R \) is the curvature scalar given by

\[ R = R(\{\}) + 4\epsilon \alpha^2(\phi) \partial_{\mu} \phi \partial^{\mu} \phi . \] (7)

It is interesting to call attention to the fact that the action in Eq.(6) is obtained from Eq.(1) by a conformal transformation of the kind

\[ \tilde{g}_{\mu\nu} = \Omega^2(\phi)g_{\mu\nu} , \] (8)

and by a redefinition of the quantity

\[ G\Omega^2(\phi) = \tilde{\phi}^{-1} . \] (7)

This transformation makes it evident that any gravitational phenomena will be affected by the variation of the gravitational constant \( G \) in the scalar-tensor gravity, a feature that is exhibited through the definition of a new parameter

\[ \alpha^2(\phi) \equiv \left( \frac{\partial \ln \Omega(\phi)}{\partial \tilde{\phi}} \right)^2 = [2\omega(\tilde{\phi}) + 3]^{-1} , \]

which can be interpreted as the field-dependent coupling strength between matter and the scalar field. In order to turn our calculations as general as possible, we will not fix the factors \( \Omega(\tilde{\phi}) \) and \( \alpha(\tilde{\phi}) \), leaving them as arbitrary functions of the scalar field.
III. ORDINARY SCS PLUS A SCALAR FIELD DYNAMICS

Let us now consider the dynamics of an ordinary SCS plus a scalar field, as the simple realization of our scenario for inducing optical activity in spacetime. In the conformal frame, the Einstein equations are modified. A straightforward calculation shows that they turn into

\[ R_{\mu\nu} = 2\xi \partial_\mu \phi \partial_\nu \phi + 8\pi G(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T) , \]

\[ G_{\mu\nu} = 2\xi \partial_\mu \phi \partial_\nu \phi - \xi g_{\mu\nu} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi + 8\pi G T_{\mu\nu} , \]

where \( \xi \) is defined as

\[ \xi(\phi) = 1 - 2\epsilon \phi^2 , \]

which contains two contributions: one coming from the scalar-tensor term and another from the torsion.

In the scalar-tensor theory the Einstein equations are modified by the presence of the field \( \phi \) and are obtained by applying the variational principle to Eq.(6). Thus, the equation describing the dynamics of the field \( \phi \) reads

\[ \Box_g \phi = -4\pi G \alpha(\phi) T , \]

where

\[ \Box_g \phi = \frac{\xi}{\sqrt{-g}} \partial_\mu \left( \sqrt{-g} \partial^\mu \phi \right) . \]

Equation(12) brings some new information because it does not appear in general relativity. It also shows us that a matter distribution in the space behaves like a source for \( \phi \), and, as usual, for \( g_{\mu\nu} \) as well. Up to now we have dealt with the purely gravitational sector, in what follows, however, we will introduce the action for the matter that describes a cosmic string.

To describe the simplest cosmic string in a scalar-tensor theory, we require the matter dynamics to be figured out from a complex scalar and a gauge field, in an Abelian Higgs model with symmetry \( U(1) \) whose action is given by

\[ I_m = \int d^4x \sqrt{g} \left[ -\frac{1}{2} D_\mu \Phi (D^\mu \Phi)^* - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V(|\Phi|) \right] , \]

where \( D_\mu \Phi = (\partial_\mu + iqA_\mu)\Phi \) is the covariant derivative, whilst \( V(|\Phi|) \) is the potential. The reason why the gauge fields do not minimally couple to torsion is well discussed in Refs. [23,27]. The field strengths are defined as usually: \( F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \), with \( A_\mu \) being the gauge field. The action given by Eq.(1) has a \( U(1) \) symmetry, where the \( U(1) \) group associated with the \( \Phi \)-field is broken by the vacuum and gives rise to vortices of the Nielsen-Olesen type \[40\] (here written in terms of \((t, r, \theta, z)\) the usual cylindrical coordinates)

\[ \Phi = \varphi(r)e^{i\theta} , \]
\[ A_\mu = \frac{1}{q}[P(r) - 1]\delta^\theta_\mu . \]

The boundary conditions for the fields \( \varphi(r) \) and \( P(r) \) are the same as those of ordinary cosmic strings \[8\], namely

\[ \varphi(r) = \eta, \ r \to \infty , \quad P(r) = 0, \ r \to \infty , \]
\[ \varphi(r) = 0, \ r = 0 , \quad P(r) = 1, \ r = 0 . \]

The potential \( V(\varphi) \) triggering the spontaneous symmetry breaking can be built as

\[ V(\varphi) = \frac{\lambda}{4}(\varphi^2 - \eta^2)^2 , \]

where \( \lambda \) is a coupling constant. Constructed in this way, this potential possesses all the ingredients that makes it viable to drive the transition leading to the formation of a cosmic string, as it is well established.

If we solve the Einstein-Cartan equations and transform to the Jordan-Fierz frame by using the conformal transformation of Eq.(8), we find that the metric of a static, straight axially symmetric SCS in scalar-tensor gravity, is given as \[11\]
\[ ds^2 = [1 + 8G_0\mu \xi^{-1} \alpha^2(\phi_0)\ln\rho/r_0][-dt^2 + dz^2 + d\rho^2 + (1 - 8G_0\mu)\rho^2 d\theta^2], \]  

where \( G_0 \) is defined as \( G_0 \equiv G\Omega^2(\phi_0) \) and we have used the fact that for a cosmic string the linearized solution of Eq.\((12)\) is given by

\[ \phi(1) = 4G_0\alpha(\phi_0)\xi^{-1}\mu \ln \frac{\rho}{r_0}. \]

The constant \( r_0 \) appearing in the Eqs.\((18)\) and \((19)\) is an integration constant, and is chosen, for convenience, as having the same order of magnitude as that of the string radius. The metric given by Eq.\((18)\) can be obtained from the one corresponding to the superconducting cosmic string \([41]\), by considering the limit when the string current vanishes.

### IV. CHERN-SIMONS-LIKE COUPLING IN A SCALAR-TENSOR SCS BACKGROUND

Recent measurements of optical polarization of light from quasars and galaxies provide evidence that in some regions on the sky the radiation polarization vectors are not randomly oriented as naturally expected, but rather they appear concentrated around a preferential direction \([3]\). These are fundamental observations that, despite the sky coverage was a bit incomplete, may hint at the spacetime as exhibiting novel properties such as the recently claimed optical activity or birefringence \([4,5]\). An interesting set of potential explanations of this effect has been put forward in Refs.\([1,4,6,7]\). Here we provide an alternative explanation of this phenomenon by considering the modification of the Maxwell action density that adds to it a Chern-Simons-like term

\[ I_{\text{eff}} = \int d^4x \sqrt{g} \left( -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} - \frac{1}{3!} \lambda \varepsilon^{\mu \nu \alpha \beta} F_{\mu \nu} A_\alpha S_\beta \right), \]

in which we couple the electromagnetic field \( F_{\mu \nu} \) and the vector potential \( A_\alpha \) to the torsion vector \( S_\beta \) (as we identify it here), responsible for the appearance of the preferred cosmic direction, as suggested by the observations \([3]\). The parameter \( \lambda \) is the coupling constant of the theory, whose likely value will be estimated later upon current astronomical data sets. Next, we will investigate the rôle played by the Chern-Simons term in the scalar-tensor screwed cosmic string background.

In this paper we will consider the case where \( S_\mu \) is a gradient of some scalar field \( \phi \) that preserves the gauge invariance but not the Lorentz invariance. In the scalar-tensor screwed cosmic string background we can consider this scalar \( \phi \) as the dilaton. Thus, by using Eq.\((3)\) the torsion vector (in the Jordan-Fierz frame) is defined as

\[ S_\mu = \frac{3}{2} \partial_\mu \ln \phi. \]

Substituting the linearized solution given by Eq.\((13)\) into Eq.\((21)\), we have

\[ S_\mu = -3\alpha(\phi_0)\partial_\mu \phi(1). \]

In this context, the field equation of the electromagnetic field becomes

\[ \frac{1}{\sqrt{-g}} \partial_\mu \left( \sqrt{-g} F^{\mu \nu} \right) = \lambda \alpha(\phi_0) \tilde{F}^{\mu \nu} \partial_\mu \phi(1). \]

The solutions of the Eq.\((23)\) give us the corresponding dispersion relation

\[ (k^\alpha k_\alpha)^2 + (k^\alpha k_\alpha)(S^\beta S_\beta) = (k^\alpha S_\alpha)^2, \]

with \( \omega \) and \( \mathbf{k} \) being the wave frequency and wave vector, respectively, and form the 4-vector \( k^\alpha = (\omega, \mathbf{k}) \); \( k = |\mathbf{k}| \). Because of the magnitude of the effect observed, we do expect \( S_\alpha \) to be small (see arguments and references in the next section) and thence we can expand the dispersion relation Eq.\((24)\) in powers of \( S_\alpha \). By using Eq.\((22)\) and substituting \( \phi(1) \) as given by Eq.\((19)\), we get, to first order, the following result

\[ k_\pm = \omega \pm 2\lambda \xi^{-1} G_0 \alpha \Omega^2(\phi_0) \sin(\gamma), \]

where \( \gamma \) is the angle between the propagation wavevector \( \mathbf{k} \) of the radiation and the unit vector \( \mathbf{s} \). We shall discuss later the relevant rôle of this wavevector components in face of the plane polarization of far out radio-galaxies and quasars. But before so doing let us generalize first this result to the case of a superconducting cosmic string.

\[ 5 \]
V. SCREWED SUPERCONDUCTING COSMIC STRING EFFECTS

We have already studied the screwed superconducting cosmic string in a recent work [11], from which further details can be obtained. In order to describe the simplest superconducting cosmic string in a scalar-tensor theory, we demand a more general matter dynamics to be constructed upon a couple of complex scalar and gauge fields, in an Abelian Higgs model whose action is written as

$$I_m = \int d^4 x \sqrt{\tilde{g}} \left[ -\frac{1}{2} D_\mu \Phi (D^\mu \Phi)^* - \frac{1}{2} D_\mu \Sigma (D^\mu \Sigma)^* - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} H_{\mu\nu\rho} H^{\mu\nu\rho} - V(|\Phi|, |\Sigma|) \right],$$

(26)

where $D_\mu \Sigma = (\partial_\mu + i A_\mu) \Sigma$ and $D_\mu \Phi = (\partial_\mu + i C_\mu) \Phi$ are the covariant derivatives. The field strengths are defined as in the standard fashion: $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $H_{\mu\nu\rho} = \partial_\mu C_{\nu\rho} - \partial_\nu C_{\mu\rho} - \partial_\rho C_{\mu\nu}$, with $A_\mu$ and $C_\mu$ being the gauge fields.

The action given by Eq.(26) has a $U(1) \times U(1)'$ symmetry, where the $U(1)$ group associated with the $\varphi$-field is broken by the vacuum and gives rise to vortices of the Nielsen-Olesen type [10]. The other $U(1)'$ symmetry, that we associate with the electromagnetism, acts on the $\Sigma$-field. This symmetry is not broken by the vacuum. It is only broken in the interior of the defect. The $\Sigma$-field in the string core, where it acquires an expectation value, is responsible for a bosonic current being carried by the gauge field $A_\mu$. The only non-vanishing components of the gauge fields are $A_z(r)$ and $A_t(r)$, and the current-carrier phase may be expressed as $\zeta(z, t) = \omega_1 t - \omega_2 z$ (see Ref. [11] for definitions). Notwithstanding, we focus only on the magnetic case. Their configurations are defined as

$$\Sigma = \sigma(r) e^{i\zeta(z, t)},$$

$$A_\mu = \frac{1}{\xi} [A(r) - \frac{\delta \zeta(z, t)}{\partial z} \delta^z],$$

(27)

because of the rotational symmetry of the string itself. The fields responsible for the cosmic string superconductivity satisfy the following boundary conditions

$$\frac{d}{dr} \sigma(r) = 0, \quad r = 0, \quad A(r) \neq 0, \quad r \to \infty,$$

$$\sigma(r) = 0, \quad r \to \infty, \quad A(r) = 1, \quad r = 0.$$

(28)

The potential $V(\varphi, \sigma)$ triggering the spontaneous symmetry breaking can be built in the most general case as

$$V(\varphi, \sigma) = \frac{\lambda_\varphi}{4} (\varphi^2 - \eta^2)^2 + f_{\varphi\varphi} \varphi^2 \sigma^2 + \frac{\lambda_\sigma}{4} \sigma^4 - \frac{m_\sigma^2}{2} \sigma^2,$$

(29)

where $\lambda_\varphi$, $\lambda_\sigma$, $f_{\varphi\varphi}$ and $m_\sigma$ are coupling constants. Constructed in this way, this potential possesses also all the ingredients so as to drive the formation of a superconducting cosmic string, as in analogy with the ordinary cosmic string case.

In order to investigate the dynamics resulting from the interaction of electromagnetic radiation from quasars and radio-galaxies with the torsion field coupled to the spacetime of background generated by the SCS in this scalar-tensor theory, as encripted by the coupling term type Chern-Simons in Eq.(20), we shall adopt the same procedure as in the last section to obtain the dilaton solution in this the superconducting case. For a superconducting cosmic string [11], the dynamics defined by Eq.(23) is complicated in itself, but if we assume that we are very far from the source then the gravitational coupling can be neglected, and so we are left with

$$\phi_{(1)} = 4 G_0 \alpha (\phi_0) \xi^{-1} (\mu + \tau - l^2) \ln \frac{\rho}{r_0},$$

(30)

Working out the dynamics of the interaction pictured by Eq.(21), we get a dispersion relation. Once again, since we expect $S_\alpha$ to be small (see sound arguments in Ref. [13]), we can expand the dispersion relation Eq.(21) in powers of $S_\alpha$ to obtain, to first order,

$$k_\pm = \omega \pm 2 \lambda \xi^{-1} G_0 (\mu + \tau - l^2) \alpha^2 (\phi_0) \xi \cos(\gamma).$$

(31)

In this case, the parameter $I$ is the current in the vortex and $\tau$ is the tension of the string.

We have already commented that the polarization of the radiation moving through an intervening magnetized intergalactic plasma must be removed from the measurements of the rotation of its polarization plane by using the fact that Faraday rotation is proportional to the square of the wavelength. In the case of the superconducting cosmic string in general relativity there is no residual polarization related to the anisotropy after removing the Faraday rotation. In this paper we show that in scalar-tensor theories of gravity, this is not the situation. In fact, the
polarization effect is present even after the Faraday rotation is removed. The scalar coupling has a current carrying contribution given by $\tau$ and the current $I$ that appear in Eq. (31).

As for the comparison with the ordinary string as the background, we note that the current $I$ has a strong negative contribution to the wavevector magnitude. This can be interpreted as if the photon has gained now a smaller wavenumber and consequently larger wavelength, and thus larger distances need to be traveled in order for the optical activity of spacetime to manifest on cosmic scales. In this case, these our results go on the same lines of those in the papers by Das, Jain and Mukherji [42] and by Kar et al. [12].

In the next section we will connect these our theoretical results with the conclusions drawn from data analysis of electromagnetic emission from radio-galaxies and quasars by Nodland and Ralston (NR97) [5]; Jain and Ralston (JR99) [7]; Das, Jain and Mukherji (DJM00) [4]; and more recently from the study of optical polarization of radio-emitting galaxies and quasars by Hutsemékers and Lamy [3]. Note that these new results by Hutsemékers and Lamy [3] appears to confirm their preliminary conclusions based on an earlier survey, and those in Refs. [4,5,7], in which they analyzed measurements of the optical polarization properties of a limited sample of broad absorption-line radio-loud and radio-intermediate high-redshift quasars [4].

VI. DISCUSSION

Let us contextualize our theoretical results in the framework of the conclusions drawn from the analysis of observational data of quasar emission performed by NR97 [5], JR99 [7] and DJM00 [4]. In the analysis of the data of high-redshift radio-emitting galaxies and quasars: about 73 in NR97, 277 in JR99, and 231 in DJM00, they found correlations between the direction on the sky and the distance to a galaxy. The angle $\beta$ between the polarization vector and the galaxy’s major axis is defined as

$$< \beta > = \frac{1}{2} \frac{r}{\Lambda_s} \cos(\vec{k}, \vec{s}),$$

where $< \beta >$ represents the mean rotation angle after Faraday’s rotation is removed, $r$ is the distance to the galaxy, $\vec{k}$ the wavevector of the radiation, and $\vec{s}$ a unit vector defined by the direction on the sky: $\equiv (315^0 \pm 30^0, 0^0 \pm 20^0)$, given here in equatorial celestial coordinates (r.a., dec.).

The rotation of the polarization plane is a consequence of the difference in the propagation speed of the two modes $\kappa_+, \kappa_-$, the main dynamical quantities computed above. This difference, defined as the angular gradient with respect to the radial (coordinate) distance, is expressed as

$$\frac{1}{2} (\kappa_+ - \kappa_-) = \frac{d\beta}{dr},$$

where $\beta$ measures the specific entire rotation of the polarization plane, per unit length $r$, and is given once again by $\beta = \frac{1}{2} \Lambda_s^{-1} r \cos \gamma$. In the case of the screwed cosmic string, the constant $\Lambda_s$, that encompasses the cosmic distance scale for the optical activity to be observed, can be written as a function of the string energy density $\mu$ as

$$\Lambda_s^{-1} = 4G_0 \mu \xi^{-1} \alpha^2 (\phi_0).$$

It is illustrative to consider a particular form for the arbitrary function $\alpha(\phi)$, corresponding to the Brans-Dicke theory, namely, $\Omega = e^{\alpha \phi}$, with $\alpha^2 = \frac{1}{\mu \Omega^2}$, ($w=cte$). Here we use the values for the scalar parameter $w > 2500$ such that the theory keeps consistent with solar system experiments made by using Very Large Baseline Interferometry (VLBI) [12]. In this case $G_0 = G_s \Omega^2 (\phi_0) = \left( \frac{\Omega^2}{\Omega^2 + \lambda^2} \right) G_{eff}$, with $G_{eff}$ the Newtonian constant. In this way, for an ordinary SCS we have the following set of constraints

$$\begin{align*}
G_0 \mu &\sim 10^{-6} & \text{from COBE data} \\
\alpha^2 &\sim 2 \times 10^{-2} & \text{Brans-Dicke gravity} \\
\xi & = 1 & \text{in our days} \\
\Lambda_s^{-1} & = 10^{-32} \text{eV} & \text{from Nodland and Ralston}
\end{align*}$$

With these observational constraints one can put a limit in the value of the coupling constant of the theory, which yields: $\lambda \sim 10^{-26}$ eV.

This result is very interesting because it shows that the optical effect could indeed be large in a theory that has a screwed cosmic string as the background in a scalar-tensor gravity, compared to the one expected from a theory that
has not it, as for instance in Refs. [11,18,19,44]. In particular, the paper by Mukhopadhyaya, Sen and SenGupta [44] shows that a very large suppression of the torsion zero-mode on the visible brane occurs in their theory, and that that suppression scales down with the Planck mass $M_P = (\hbar c/G_N)^{1/2} \sim 10^{19}$ GeV. This means that their coupling constant is $\sim 10^{-28}$ eV. This suppression scale is two orders of magnitude smaller than the strength of coupling attained in the present theory. In this way we show that the general scalar-tensor theory in the SCS background with torsion can give an interesting explanation to these observational data regarding the occurrence of optical activity in the spacetime spanning over cosmological distances. And more interesting yet, the result attained shows that the torsion field effect is more stronger than the one contemporary wisdom believed, and that it may indeed be being detected through this spacetime birefringence and optical activity phenomenology. This is a new view point as opposite to the one presented in Ref. [14], where the illusion of a torsion-free universe appears to be supported in the framework of braneworld physics.

If both, the cosmological anisotropy that Nodland and Ralston [1]; Jain and Ralston [4]; and Das et al. (DJM00) [4] have claimed to exist in the direction (NR97) $\hat{s} = (|21 \pm 2| \mathrm{hrs}, 0^\circ \pm 20^\circ)$ (r.a.,dec.), and the optical activity of spacetime evidenced in the Hutsemékers and Lamy [3] surveys of quasar optical polarization vectors, are real, then they may reconcile these modern observations with earlier ones [13,45,46]. Although this birefringence phenomenon was contentious [18,45,46], at the moment its occurrence is vastly demonstrated [2,3,4,5,7]. Indeed, JR99 [7] and DJM00 [4] suggested that the effect, which is clearly visible for the two highest redshifts in the DJM00 data set, would be more decisively demonstrated, as already pointed out by Carroll and Field [3], when new data from very distant galaxies are incorporated to the sample. Thus, there seems to be room for viable explanations of the origin of such a preferred direction on the sky [3,18].

VII. CLOSING REMARKS

In the present paper we consider the possibility of explaining the quoted polarization effects in the framework of scalar-tensor gravity theories that couples to torsion. In our approach a screwed cosmic string, defining the background spacetime on which the interaction between the electromagnetic and torsion fields may take place, is able to create a propagating effect which may manifest outside the string itself. In this sense, being the effect or phenomenon a real one, this model may also provide a consistent description of the NR97, JR99 and DJM00 conclusions by endowing the cosmic string spacetime with torsion. In fact, a possible connection of this effect with the existence of a cosmic rotation axis was pointed out in [18,46], who suggested the discovery of a cosmic axis in NR97, and claimed that the observed phenomenon may be a realization of an ancient theoretical idea already presented in Gödel’s cosmology. An alternative mechanism was envisioned by Dobado and Maroto who proposed that the effect, if real, may be interpreted through the coupling of the electromagnetic field with a background torsion field created by charged fermions [19]. Although a viable proposal, this suggestion exhibits a fundamental drawback: it is implicit that the sea of fermions is isotropically distributed in spacetime. Thence, the effect must be present in any other direction on the sky! Unfortunately, observations do not support this assumption. In addition, the model should also be put forward a bit further to cope with additional observational implications of the existence of such a chiral background of relic particles. This crucial constraint was overlooked in that paper. Meanwhile, the spacetime with torsion produced by the Kalb-Ramond field coupled gravitationally to the Maxwell field, in the heterotic string-inspired model of Ref. [11] (and references therein), appears also to be a very sound proposal for explaining the origin of the optical activity observed in the synchrotron radiation received from cosmic radio-galaxies and quasars. Once again, the mechanism suggests the just quoted isotropic effect, which not stands on the quoted observations evidencing the existence of a preferred direction on the sky. Moreover, there are several well-known open issues in the string theory used for that leaves the mechanism not fully solidly fundamented.

Put the other way round, our theory is able to provide a consistent explanation for the occurrence of these phenomena regarding the curious propagation of electromagnetic waves over cosmic distances. Concomitantly, the theory can account also for the peculiar alignment of the spin axes observed in galaxies belonging to the supercluster Perseus-Piscis [18,45,46]. If confirmed, this cosmic effect might prove an indication of the existence of a universal torsion (or shear) field and an universal spin, as well. We consider as a possible origin of such an effect the coupling between electromagnetic fields and some torsion field, as described by Eq. (20), in the background of a screwed cosmic string in scalar-tensor gravity theories, with no fermion fields. The use of alternative gravity theories is justified by the fact that Einstein’s gravitation does not admit this sort of phenomenology, and consequently cannot provide any explanation to this puzzle. In this approach the screwed cosmic string background can be source of optical activity of spacetime even if the string has no spin. In a screwed cosmic string background the medium can be birefringent too due to the appearance of a torsion-dependent deficit angle, and this feature may induce an interaction of the electromagnetic radiation with a scalar gradient by
means of a Chern-Simons coupling. In this way, we can explain the optical activity without invoking an universal sea of either fermionic or axion-like matter pervading the spacetime as its source, as considered by other authors. At the same time, the fact that this theory is concomitant with several experiments and astronomical observations may hint at a gravitation theory beyond Einstein’s general relativity.

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