
Indonesian Physical Review

Volume 08 Issue 01, January 2025

P-ISSN: 2615-1278, E-ISSN: 2614-7904

A weak gravitational knot in (2+1)-dimensional empty space-time

Miftachul Hadi^{1,2,3*}, Suhadi Mulyono^{4*}

¹ Badan Riset dan Inovasi Nasional (BRIN), KST Habibie (Puspipstek) Gd 442, Serpong, Tangerang Selatan, Banten, Indonesia

² Institute of Mathematical Sciences, Bogor, Jawa Barat, Indonesia

³ Institute of Natural Sciences, Krajan, Madiun, Jawa Timur, Indonesia

⁴ Jurusan Fisika FMIPA, Universitas Mulawarman, Samarinda, Kalimantan Timur, Indonesia

Corresponding Authors E-mail: instmathsci.id@gmail.com, gusmulfisika@gmail.com

Article Info

Article info:

Received: 11-06-2024

Revised: 07-12-2024

Accepted: 28-12-2024

Keywords:

(2+1) gravity theory;
empty space-time;
cosmological constant;
weak-field limit; Abelian
Chern-Simons action;
gravitational knot

How To Cite:

M. Hadi and S. Mulyono,
"A weak gravitational knot
in (2+1)-dimensional
empty space-time",
Indonesian Physical
Review, vol. 8, no. 1, p
238-252, 2025.

DOI:

<https://doi.org/10.29303/ipr.v8i1.346>

Abstract

We propose the existence of a topological object, a weak gravitational knot, in the framework of an Abelian Chern-Simons action with a small positive cosmological constant in (2+1)-dimensional empty space-time.



Copyright (c) 2025 by Author(s). This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

Introduction

It has been widely believed that topological objects cannot exist in linear theories. Topological theories are inherently non-linear [1]. How could a topological object, like a gravitational knot, exist in linear theory, such as an Abelian Chern-Simons theory?

It is well known that the general theory of gravitation is identical to a gauge theory [2-6]. Maxwell's theory of electromagnetism and Einstein's theory of gravitation are identical, where the gauge potential and the field strength tensor in Maxwell's theory (in general, a non-Abelian

gauge theory, such as Yang-Mills theory) are identical to the connection and the curvature in general relativity, respectively [2]. Both theories are gauge theories, where Maxwell's theory is an Abelian $U(1)$ gauge theory of internal space, and general relativity can be treated as the gauge theory of translation of (3+1)-dimensional (external) space-time [3]. The vierbein formalism of general relativity (Cartan gravity) makes general relativity similar to a gauge theory [4]. Nevertheless, general relativity and a gauge theory are not equivalent to (3+1)-dimensional space-time. But they are precisely equivalent in (2+1)-dimensional space-time [4].

Roughly speaking, gravity theory in (2+1)-dimensional space-time is a simpler model than general relativity in (3+1)-dimensional space-time. Gravity theory in (2+1)-dimensional space-time shares the important conceptual features of general relativity in (3+1)-dimensional space-time while avoiding some computational difficulties. As a generally covariant theory of space-time, (2+1)-dimensional gravity has the same conceptual foundation as realistic (3+1)-dimensional general relativity [5].

With a few exceptions, (2+1)-dimensional solutions are physically quite different from those in 3+1 dimensions. The (2+1)-dimensional model is not very helpful for understanding the dynamics of realistic quantum gravity. However, the model has proven highly instructive for analyzing conceptual problems, e.g., the nature of time, the construction of states and observable, the role of topology, and topology change [5]. The dynamics is topology in (2+1)-dimensional spacetime gravity [7]. The (2+1)-dimensional gravity theory could be interpreted as a Chern-Simons three form [4]. The Chern-Simons theory is a topological gauge theory in (2+1)-dimensional spacetime [7], where the Chern-Simons action precisely coincides with the (2+1)-dimensional space-time of the Einstein-Hilbert action [4, 6].

The Einstein-Hilbert action in (2+1)-dimensional space-time, without a cosmological constant, is equivalent to a gauge theory with gauge group $ISO(2,1)$ and a pure Chern-Simons action [4]. If we include a cosmological constant in (2+1) general relativity, then Minkowski (flat) space-time is replaced by space-time with a constant curvature: de Sitter or anti-de Sitter depending on the sign of a cosmological constant (plus for de Sitter and minus for anti-de Sitter), and gauge group $ISO(2,1)$ is replaced by $SO(3,1)$ or $SO(2,2)$ [4].

Suppose the relation between general relativity and Chern-Simons gauge theory is valid at the quantum level. In that case, there is a close relationship between general relativity and knot theory, at least in (2+1)-dimensional space-time, since Chern-Simons gauge theory in (2+1)-dimensional space-time is intimately connected with knot theory [4]. We consider the quantum level here to be related to the topological quantum condition, the discreteness.

The formulation of a gravitational knot for a non-Abelian Chern-Simons action in (2+1)-dimensional empty space-time has been proposed [4, 6-9]. In this article, we propose the existence of a gravitational knot in the weak-field limit in (2+1)-dimensional empty spacetime formulated as an Abelian Chern-Simons action with a small positive cosmological constant written using the Clebsch variables. To the best of our knowledge [1, 4, 6-16], the formulation of such weak gravitational knot has not been done yet.

We assume that a topological structure in three-dimensional gravity is similar to that in Maxwell's theory of vacuum space [1]. Analogous to the linearized Ricci curvature tensor in (3+1)-dimensional space-time, the linearized Ricci curvature tensor (with a small positive cosmological constant) in the case of the weak-field limit is assumed to be valid in (2+1)-dimensional space-time.

In analogy to Maxwell's theory of vacuum space, where the field strength tensor could consist of a set of subset fields [1, 17], complex scalar fields, we propose that the Ricci curvature tensor (the set of the solutions of Einstein field equations) could consist of a set of curvature components, complex scalar potentials. This curvature component set, such as subset fields, satisfies the non-trivial Hopf maps. This means that non-trivial Hopf maps can describe the properties of a set of curvature components.

A set of curvature components is locally equal to the linearized Ricci curvature tensor, i.e. the linearized Ricci curvature tensor can be obtained by patching together a set of curvature components (except in a zero-measure set) but globally different. The difference is global instead of local since a set of curvature components obey the topological quantum condition, but the linearized Ricci curvature tensor does not. The linearized Ricci curvature tensor satisfies the linear Ricci theory, but a set of curvature components satisfies the non-linear Ricci theory. The linearized Ricci curvature tensor and a set of curvature components satisfy the linear Ricci theory in the case of a weak-field limit. This means that, in the case of a weak-field limit, the non-linear Ricci theory is reduced to the linear Ricci theory.

This article is organized as follows. Section II briefly discusses the (3+1)-dimensional gravity in the case of sourceless and without a cosmological constant. In Section III, the (2+1)-dimensional gravity in the case of sourceless, without and with a cosmological constant. Section IV identifies the relation between the Einstein-Hilbert and the Chern-Simons actions in (2+1)-dimensional space-time. Section V discusses linearized metric perturbations, scalar, and vector potentials. Section VI briefly discusses a set of curvature components and Hopf maps. Section VII discusses the Hopf invariant, Hopf index, and Chern-Simons action. Section VIII, we formulate the non-linear and linear Ricci theories using complex scalar potentials and vector potential in terms of the Clebsch variables. Section IX describes the relation between the gauge potential and the gauge fields. We formulate the gauge fields in terms of Clebsch variables. In Section X, we formulate the weak gravitational knot. In Section XI, a discussion and conclusion are given.

(3+1) Gravity

The Einstein field equations in (3+1)-dimensional space-time can be written as

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \quad (1)$$

where

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \quad (2)$$

$G_{\mu\nu}$ is Einstein tensor, $R_{\mu\nu}$ is the Ricci curvature tensor, $g_{\mu\nu}$ is metric tensor, R is the Ricci scalar curvature, Λ is a cosmological constant, G is the gravitational coupling constant (the generalization to other dimensions of Newton's constant) [8], $T_{\mu\nu}$ is the energy-momentum tensor of matter.

In this paper, what we mean by an empty space-time is a vacuum space-time, $R_{\mu\nu} = 0$, where there is no matter the source present, $T_{\mu\nu} = 0$, and no physical fields exist except the gravitational field [18]. This gravitational field does not disturb the emptiness, but other fields do [18]. Einstein assumed that in (3+1)-dimensional empty space-time, it constitutes his law of gravitation [18].

In the absence of matter and without cosmological constant, the Einstein field equations (1), (2) read [9]

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0 \quad (3)$$

In general, the vanishing of $G_{\mu\nu}$ hence of $R_{\mu\nu}$ and R , does not imply that the Riemann curvature tensor is zero, i.e. the space-time need not be flat [9]. However, the situation is different in (2+1)-dimensional space-time.

(2+1) Gravity

In (2+1)-dimensional space-time manifold, M , Einstein-Hilbert action for gravity coupled to matter can be written as [5, 19]

$$I_{EH} = \frac{1}{16\pi G} \int_M d^{2+1}x \sqrt{-g} (R - 2\Lambda) + I_{matter} \quad (4)$$

where $g = \det(g_{\mu\nu})$ is the determinant of the metric tensor matrix.

Equation of motion for the action (4) is [5, 19]

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = -8\pi G T_{\mu\nu} \quad (5)$$

We see that the equation of motion (5) is the same as (1). Eq. (5) are generally covariant, i.e. they are invariant under the action of the group of diffeomorphisms (which can be viewed as a gauge group) of the spacetime [5]. A diffeomorphism is a smooth (continuously differentiable), reversible transformation between spaces or shapes that preserves their smooth structure. In contrast, an isometry [20] (distance-preserving mapping) is a special case of a diffeomorphism.

In (2+1)-dimensional space-time, the relation between the Einstein tensor and the Riemann curvature tensor can be written as [9]

$$G_{\nu}^{\mu} = -\frac{1}{4} \varepsilon^{\mu\alpha\beta} \varepsilon_{\nu\gamma\delta} R_{\alpha\beta}^{\gamma\delta} \quad (6)$$

where $\varepsilon^{\mu\alpha\beta}$ is Levi-Civita symbols, μ, α, β , denote spacetime coordinates. Eq. (6) may be inverted as [8]

$$R_{\beta\nu}^{\alpha\mu} = \varepsilon^{\alpha\mu\gamma} \varepsilon_{\beta\nu\delta} G_{\gamma}^{\delta} \quad (7)$$

Eqs. (6) and (7) are the identities linking the Einstein tensor and the Riemann curvature tensor.

Eq. (7) without a cosmological constant implies that if the Einstein tensor vanishes (due to the absence of matter), then the Riemann curvature tensor vanishes. In turn, the vanishing Riemann curvature tensor implies that the Ricci curvature tensor and the Ricci curvature scalar are equal to zero. So, the solution of eq. (7) is flat space-time. We call the theory trivial, i.e. it does not possess any propagating degrees of freedom [9].

For an empty space-time and a non-zero cosmological constant, eq. (5) can be replaced by

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 0 \quad (8)$$

and by substituting eq. (8) into eq. (7), we obtain [9]

$$R_{\alpha\mu\beta\nu} = -\Lambda (g_{\alpha\beta} g_{\mu\nu} - g_{\alpha\nu} g_{\beta\mu}) \quad (9)$$

which shows that without sources, all spaces that solve (8) are of constant curvature: a closed de Sitter space for $\Lambda > 0$ or a hyperbolic anti-de Sitter space for $\Lambda < 0$ [9]. We consider that the constant curvature indicates that the geometry of space-time is locally homogeneous [4] and isotropic in the sense that curvature is uniform.

Eq. (8) implies that the Ricci curvature tensor can be written as

$$R_{\mu\nu} = \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} \quad (10)$$

It means that the Ricci curvature tensor is not simply proportional to the metric tensor, $g_{\mu\nu}$, scaled by a constant R , but also has an additional term involving the cosmological constant.

Einstein-Hilbert Action as Chern-Simons Action

Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference. Only relevant modifications should be described.

The Einstein-Hilbert action without a cosmological constant

The Einstein-Hilbert action without a cosmological constant in (2+1)-dimensional space-time manifold would be [4]

$$I_{EH} = \frac{1}{2} \int_M \varepsilon_{\mu\nu\rho} \varepsilon_{abc} e_\mu^a \left(\partial_\nu \omega_\rho^{bc} - \partial_\rho \omega_\nu^{bc} + [\omega_\nu, \omega_\rho]^{bc} \right) d^{2+1}x \quad (11)$$

where e_μ^a is a dreibein, ω_ρ^{bc} is a spin connection, ε_{abc} is the Levi-Civita symbols in the internal (local Lorentz frame) space. If a dreibein and a spin connection are interpreted as gauge fields, it might conceivably be interpreted (11) as a Chern-Simons action [4].

From eq. (11), the Ricci curvature tensor can be written as

$$R_{\nu\rho}^{bc} = \partial_\nu \omega_\rho^{bc} - \partial_\rho \omega_\nu^{bc} + [\omega_\nu, \omega_\rho]^{bc} \quad (12)$$

Eq. (12) is a non-linear equation. The commutation relation in the third term of the right-hand side shows the nonlinearity, $[\omega_\nu, \omega_\rho]^{bc}$. This commutation term represents the self-interaction of the spin connection.

The Chern-Simons action without a cosmological constant

The Chern-Simons action in (2+1)-dimensional spacetime manifold can be written as [4,8]

$$I_{CS} = \int_M \varepsilon^{\mu\nu\rho} e_{\mu a} \left(\partial_\nu \omega_\rho^a - \partial_\rho \omega_\nu^a + \varepsilon_{bc}^a \omega_\nu^b \omega_\rho^c \right) d^{2+1}x \quad (13)$$

We raise the a index in ε_{bc}^a to show explicitly the contraction of the index. The Chern-Simons action (13) precisely coincides with the Einstein-Hilbert action (11) [4].

The Einstein-Hilbert action with a cosmological constant

The generalized Einstein-Hilbert action in (2+1)-dimensional space-time with a non-zero cosmological constant can be written as [4]

$$I_{EH} = \int_M \varepsilon^{\mu\nu\rho} \left\{ \varepsilon_{\mu\alpha} (\partial_\nu \omega_\rho^\alpha - \partial_\rho \omega_\nu^\alpha) + \varepsilon_{abc} e_\mu^a \omega_\nu^b \omega_\rho^c + \frac{\Lambda}{3} \varepsilon_{abc} e_\mu^a e_\nu^b e_\rho^c \right\} \quad (14)$$

The equations of motion (14) say that space-time is not flat but locally homogeneous, with the curvature proportional to a cosmological constant [4].

The connected covering space of such a spacetime is not a portion of Minkowski space but a portion of de Sitter or anti-de Sitter space. The spaces of de Sitter and anti-de Sitter have $SO(3,1)$ and $SO(2,2)$ for their symmetries, respectively. It is different from the flat space-time of Minkowski, which has its symmetry $ISO(2,1)$ [4]. Thus, it is reasonable to guess that if the gravity theory without a cosmological constant in (2+1)-dimensional space-time is related to the gauge theory of $ISO(2,1)$, then the gravity theory with a cosmological constant in (2+1)-dimensional space-time will be related to gauge theory of $SO(3,1)$ and $SO(2,2)$ [4].

We see from eq. (14), the Ricci curvature tensor could be written as [6]

$$R_{\nu\rho}^a = \partial_\nu \omega_\rho^a - \partial_\rho \omega_\nu^a + \varepsilon_{bc}^a \omega_\nu^b \omega_\rho^c + \frac{\Lambda}{3} \varepsilon_{bc}^a e_\nu^b e_\rho^c \quad (15)$$

In terms of the spin connection, eq. (15) is a non-linear equation due to there exists the multiplication term of the spin connection in the third term of the right-hand side, $\omega_\nu^a, \omega_\rho^a$ such as in eq. (12).

The weak-field limit and a small positive cosmological constant

In the case of the weak-field limit of the gauge fields and a small positive cosmological constant, $\Lambda > 0, |\Lambda| \ll 1$, eq. (15) reduces to a linearized Ricci curvature tensor written below

$$R_{\nu\rho}^a = \partial_\nu \omega_\rho^a - \partial_\rho \omega_\nu^a + \frac{\Lambda}{3} \varepsilon_{bc}^a e_\nu^b e_\rho^c \quad (16)$$

In terms of the spin connection, eq. (16) is a linear equation. There is no self-interaction of the spin connection. Although, at first sight, eq. (16) looks like a non-linear equation, because a quadratic form exists (as a product of the dreibein components) in the third term of eq. (16). Here, the dreibein components can be viewed as the fixed fields, i.e., the fields that are considered given or fixed externally, parameters. They are not variables being solved for. The fixed dreibein fields, due to a cosmological constant, introduce a source term imposed on the curvature.

The Chern-Simons action with a cosmological constant

The generalized (non-Abelian) Chern-Simons action with a non-zero cosmological constant could be written as [4, 6]

$$I_{CS} = \int_M \varepsilon^{\mu\nu\rho} e_{\mu\alpha} \left\{ \partial_\nu \omega_\rho^\alpha - \partial_\rho \omega_\nu^\alpha + \varepsilon_{bc}^a \left(\omega_\nu^b \omega_\rho^c + \frac{\Lambda}{3} e_\nu^b e_\rho^c \right) \right\} d^{2+1}x \quad (17)$$

From eq. (17), the Ricci curvature tensor can be written as

$$R_{\nu\rho}^a = \partial_\nu \omega_\rho^a - \partial_\rho \omega_\nu^a + \varepsilon_{bc}^a \left(\omega_\nu^b \omega_\rho^c + \frac{\Lambda}{3} e_\nu^b e_\rho^c \right) \quad (18)$$

We see that eq. (18) is equivalent to eq. (15).

Regarding the weak-field limit of the gauge fields and a small positive cosmological constant, eq. (18) reduces to a linearized Ricci curvature tensor written below

$$R_{\nu\rho}^a = \partial_\nu\omega_\rho^a - \partial_\rho\omega_\nu^a + \frac{\Lambda}{3} \varepsilon_{bc}^a e_\nu^b e_\rho^c \quad (19)$$

where ε_{bc}^a the Levi-Civita symbol has a role as the structure constants (the structure coefficients) [21]. Eq. (19) is a linear equation regarding the spin connection. The reason is analogous to eq. (16).

The Abelian Chern-Simons action with a cosmological constant

The Abelian Chern-Simons action with a small positive cosmological constant can be obtained from eq. (17) By replacing the Ricci curvature tensor (18) with a linearized Ricci curvature tensor (19), we have

$$I_{CS} = \int_M \varepsilon^{\mu\nu\rho} e_{\mu a} \left(\partial_\nu\omega_\rho^a - \partial_\rho\omega_\nu^a + \frac{\Lambda}{3} \varepsilon_{bc}^a e_\nu^b e_\rho^c \right) d^{2+1}x \quad (20)$$

We will use this Abelian Chern-Simons action (20) to formulate the gravitational knot.

Linearized Metric Perturbations, Scalar and Vector Potentials

The linearized (small) metric perturbations can be written as

$$h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu} \quad (21)$$

where $\eta_{\mu\nu}$ is the metric of Minkowski (flat) space-time. The small metric perturbations means that $|h_{\mu\nu}| \ll 1$ for all μ and ν .

In the language of a wave, the linearized metric perturbations can be written as [22]

$$h_{\mu\nu} = \rho_{\mu\nu} e^{i\mathbf{k}\cdot\mathbf{r}} \quad (22)$$

where $\rho_{\mu\nu}$ is the amplitude as a function of space-time, \mathbf{k} is the wave vector, \mathbf{r} is the position vector, and $\mathbf{k}\cdot\mathbf{r}$ is the phase, a function of space-time. In an empty space-time, the amplitude is constant.

In the linearized gravity theory, the linearized metric perturbations take a role as “potentials” [22]. We consider the linearized metric perturbations analogous to a set of curvature components, the scalar potentials, which could be complex, written as [23]

$$h = \rho e^{iq}, \quad h^* = \rho e^{-iq} \quad (23)$$

where ρ is the amplitude, q is the phase, h^* is the complex conjugate of h , i is an imaginary number. Both the amplitude and the phase are the functions of space-time.

The related (real) vector potential could be written as

$$h_\mu = f \partial_\mu q \quad (24)$$

where the Greek index, μ , denotes the spatial index, f is the amplitude function written below

$$f = -\frac{1}{\{2\pi(1+\rho^2)\}} \quad (25)$$

Here f and q are the Clebsch variables [24] or the Gaussian potentials [8, 25]. Both f and q are scalars.

In the following, we will interpret the gauge potential in a gauge theory as the gauge fields (the dreibein and the spin connection) in general relativity. We will then reformulate the relation between the gauge potential and the gauge fields written using the Clebsch scalar

variables. First, it is necessary to show that a set of curvature components satisfies the non-trivial Hopf maps.

A Set of Curvature Components and Hopf Maps

The properties of the complex scalar potentials could be described by the non-trivial Hopf maps written below

$$h(\mathbf{r}), h^*(\mathbf{r}): S^3 \rightarrow S^2 \quad (26)$$

These non-trivial Hopf maps can be classified into homotopy classes labeled by the value of the corresponding Hopf indexes, integer numbers, and topological invariants [1, 17]. The other names of the topological invariants are the topological charge and the winding number (the degree of a continuous mapping, such as the Hopf maps). The topological charge is metric tensor-independent, it can be interpreted as energy [26].

The complex scalar potentials in the non-trivial Hopf maps (26) are time independent. Analogous to the time-independent complex scalar fields, this problem could be solved by interpreting some of the quantities that appear in Hopf's theories as Cauchy's initial time values [24]. We consider that the two-dimensional spheres, S^2 , as codomain in the Hopf maps, could be interpreted as two-dimensional spheres with constant curvature. We will interpret these two-dimensional spheres with constant curvature as de Sitter space.

Hopf Invariant, Hopf Index, Chern-Simons Action

The Hopf invariant, H , can be expressed as [15, 27, 28]

$$H = \int_{S^3} \varepsilon^{\mu\nu\rho} \Omega_\mu \partial_\nu \Omega_\rho d^3x \quad (27)$$

where Ω_μ can be interpreted as a connection one-form, a gauge potential, d^3x represents the volume element on S^3 . In hydrodynamics, this partial derivative of connection one-form, $\partial_\nu \Omega_\rho = W_{\nu\rho}$, can be interpreted as the vorticity.

The Hopf invariant can be related to the Hopf index, \mathcal{H} , written explicitly as [1]

$$H = \mathcal{H} \gamma^2 \quad (28)$$

where γ is the total strength of the field [1].

The concept of the Hopf invariant arises naturally from the geometry of the Hopf maps. It measures the degree (number) of linking of the preimages on S^3 mapped to a point on S^2 under the Hopf maps. The linking number tells us how often one of these loops wraps around the other. If the linking (integer) number is zero, there is no entanglement between two loops. These two loops can be separated or untangled without cutting. We could call these two separated loops the distant union of two unknots (the unknot is the knot) which is a perfectly fine link. This is because links do not need to be linked [29]. If the linking number is not zero, then there exists an entanglement in the Hopf maps, the (continuous) non-trivial maps.

The Hopf invariant is identical to the circulation in hydrodynamics [25], where Ω and $d\Omega$ in the Hopf invariant are identical to the velocity field and the vorticity in hydrodynamics, respectively. Suppose we relate hydrodynamics (self-helicity) to a gauge theory. In that case, it can be interpreted naturally that the Hopf invariant has a deep relationship with the Chern-Simons action (the Chern-Simons integral) [15]. The Hopf invariant is just the winding number

of Gauss mapping [15]. The Hopf invariant is an important topological invariant in describing the topological characteristics of the knot family. More precisely, the Hopf invariant or the Chern-Simons action is the total sum of all the linking and all the self-linking numbers of the knot family [15,16]. The linking and self-linking numbers by themselves have a topological structure.

Non-Linear and Linear Ricci Theories

Analogous to a non-linear field theory in Maxwell's theory [1], the non-trivial Hopf maps (26) have a consequence that we could write a non-linear Ricci theory as

$$R_{\mu\nu} = \frac{\sqrt{s}}{2\pi i} \left\{ \frac{\partial_\mu h^* \partial_\nu h - \partial_\nu h^* \partial_\mu h}{(1 + h^* h)^2} \right\} \quad (29)$$

where s is an action constant, introduced so that the nonlinear Ricci theory (written using the complex scalar potentials) will have suitable dimensions for the curvature. The nonlinearity of eq. (29) is shown by the $h^* h$ term in the denominator.

In the case of a weak-field limit, the complex scalar potentials are very small, $|h^* h| \ll 1$, so eq. (29) reduces to a linear Ricci theory as written below

$$R_{\mu\nu} = \frac{\sqrt{s}}{2\pi i} (\partial_\mu h^* \partial_\nu h - \partial_\nu h^* \partial_\mu h) \quad (30)$$

If eq. (30) is written using the (real) vector potential (24), then we obtain

$$R_{\mu\nu} = \frac{\sqrt{s}}{2\pi i} (\partial_\mu h_\nu - \partial_\nu h_\mu) \quad (31)$$

This linear Ricci theory (31) is equivalent to the linearized Ricci curvature tensor [30, 31]

$$R_{\mu\nu} = \partial_\alpha \Gamma_{\mu\nu}^\alpha - \partial_\nu \Gamma_{\mu\alpha}^\alpha \quad (32)$$

It means that the linearized Ricci curvature tensor (32) could be interpreted the same as the linear Ricci theory (31).

By using the vector potential (24), the linear Ricci theory (31) could be written as

$$R_{\mu\nu} = \frac{\sqrt{s}}{2\pi i} \{ \partial_\mu (f \partial_\nu q) - \partial_\nu (f \partial_\mu q) \} \quad (33)$$

This is the linear Ricci theory written regarding the Clebsch scalar variables. The vector potential written using the Clebsch variables (33) is equivalent to the Levi-Civita connection (the Christoffel symbols) in eq. (32).

Gauge Potential and Gauge Fields

In the dreibein formalism of general relativity, we have the gauge fields (the dreibein and the spin connection). These gauge fields could be viewed identically to the gauge potential. In this case, the gauge potential can be written as [4, 6, 8]

$$A_\mu = e_\mu^a P_a + \omega_\mu^a J_a \quad (34)$$

where e_μ^a is a component of the vierbein (the translational part), $e_\mu^a P_a$ is the vierbein field or shortly the vierbein, ω_μ^a is a component of the spin connection (the rotational part), $\omega_\mu^a J_a$ is the spin connection field or the spin connection, P_a, J_a , are the generators of translation and rotation, respectively.

Analogous to (24), we could write the gauge potential as

$$A_\mu = f \partial_\mu q \tag{35}$$

By substituting eq. (35) into eq. (34), we obtain

$$f \partial_\mu q = e_\mu^\alpha P_\alpha + \omega_\mu^\alpha J_\alpha \tag{36}$$

If we assume that the components of the vierbein and the spin connection could be written using the Clebsch variables, they could be written respectively, as

$$e_\mu^\alpha = f_e \partial_\mu q_e^\alpha \tag{37}$$

and

$$\omega_\mu^\alpha = f_\omega \partial_\mu q_\omega^\alpha \tag{38}$$

where f_e, f_ω , are the amplitude functions of the vierbein and the spin connection, respectively. Both of them relate to gravitational “strength” or scaling effects, i.e. they scale the contributions of $\partial_\mu q_e^\alpha$ and $\partial_\mu q_\omega^\alpha$. $q_e^\alpha, q_\omega^\alpha$, are the phase of the vierbein and the spin connection, respectively. Their gradient encodes information about the direction or orientation of the gravitational field.

By substituting eqs. (37), (38), into (36), the gauge potential becomes

$$f \partial_\mu q = f_e \partial_\mu q_e^\alpha P_\alpha + f_\omega \partial_\mu q_\omega^\alpha J_\alpha \tag{39}$$

where the amplitude functions of the vierbein and the spin connection are constant due to the amplitude in an empty space-time is constant.

A Weak Gravitational Knot

By substituting eqs. (37), (38), into eq. (20), and by assuming that f_e, f_ω , are constants, we obtain the Abelian Chern-Simons action in (2+1)-dimensional space-time as written below

$$I_{CS} = \int_M \varepsilon^{\mu\nu\rho} f_e \partial_\mu q_{ea} \left\{ f_\omega (\partial_\nu \partial_\rho - \partial_\rho \partial_\nu) q_\omega^a + \frac{\Lambda}{3} \varepsilon_{bc}^a f_e \partial_\nu q_e^b f_e \partial_\rho q_e^c \right\} d^{2+1}x \tag{40}$$

The Chern-Simons action (40), could be interpreted as a weak gravitational knot. The Levi-Civita symbols have a role as structure constants that couple the interaction between the gauge fields. The amplitude functions, f_e, f_ω , have a role as scale factors. We see that the Chern-Simons action (40) is identical to the Hopf invariant [27]. This weak gravitational knot is an integer number. That is what we mean by a set of curvature components obeying the topological quantum condition.

Discussion and Conclusion

It has been realized that topology's role has become increasingly important in recent days and the future of physics. But to understand topology is complicated enough because topology is inherently related to nonlinearity. It has been widely believed that topological objects cannot exist in linear theories, such as an Abelian Chern-Simons action in the topological quantum field theory. But this belief can no longer be maintained. The discovery of the electromagnetic knot in vacuum Maxwell's theory more than thirty years ago has shown that the topological object could exist in the linear theory.

We adopt the idea [1] of the electromagnetic knot and apply it to gravity. This is because electromagnetism and gravity are similar. The electromagnetic or Maxwell's theory is a gauge theory and gravity theory (the general theory of relativity) could be treated as a gauge theory.

Maxwell's theory is an Abelian $U(1)$ local gauge theory of internal space and general relativity, a non-linear theory, is a gauge theory of translation in (3+1)-dimensional (external) space-time. The gauge potential and the field strength tensor in electromagnetism are identical to the connection and the curvature in gravity theory, respectively.

In (2+1) empty space-time, the curvature can be nonzero due to a non-zero cosmological constant. This (constant) curvature causes the gravitational fields to interact with themselves, as shown by the term $\frac{\Lambda}{3} \varepsilon_{abc} e_{\mu}^a e_{\nu}^b e_{\rho}^c$ (14) and its equivalent form in a gauge theory (17), giving rise to non-trivial topological objects, such as gravitational knots. The gravitational field can be visualized as a string to form a closed loop, a knot. These knots are localized in space-time because they relate to the interaction between gravitational fields or curvature that occur locally.

We propose that curvature, i.e., the Ricci theory, has a set of curvature components. We consider this set of curvature components analogous to the linearized (small) metric perturbations, i.e. a set of curvature components could consist of the scalar potentials. It is because the linearized metric perturbations take a role as potentials, i.e., the linearized metric perturbations are the scalar potentials. A set of curvature components could be complex; for example, in the case of the electromagnetic knot, a set of subset fields could consist of complex scalar fields. Consequently, the complex scalar potential could be interpreted equivalently as the complex scalar fields. In other words, a set of curvature components could be interpreted equivalently as the complex scalar fields. It means that, roughly speaking, the curved space-time could be treated as complex fields. What does it imply?

The scalar potentials, such as the scalar fields, could be described using wave language. Both could be denoted by the amplitude times the exponential of iq , where q is the phase, and i is the imaginary number. The related (real) vector potential can be written using the Clebsch (scalar) variables f and q (24). We chose the real part of the related vector potential because we still do not know the consequence of the imaginary part formulation in physics.

The Clebsch variables are not uniquely defined, but they can make many choices. In this way, the vector potential can be understood simply. These Clebsch variables are related to any divergenceless vector field, i.e. the divergence of any vector field gives the zero result. Examples of a divergenceless vector field are the vorticity in hydrodynamics, i.e. $\nabla \cdot \mathbf{W} = 0$, so $\mathbf{W} = \nabla \times \mathbf{v}$ where \mathbf{v} is the velocity field vector, and in electromagnetism $\nabla \cdot \mathbf{B} = 0$, $\mathbf{B} = \nabla \times \mathbf{A}$ where \mathbf{B} is the magnetic field, \mathbf{A} is the potential.

The condition $\nabla \cdot \mathbf{B} = 0$ implies that vorticity is solenoidal, meaning it is sourceless or has no sinks. The vorticity originates from the curl of the velocity field. This means that the "source" of vorticity is the rotational motion of the velocity field rather than a scalar charge such as in electromagnetism. We can observe the non-zero vorticity phenomenon in the rotational flows of fluids, e.g. a whirlpool. We see from eqs. (20), (40), the vorticity is identical to the curvature, and the velocity field is identical to the gauge fields (the dreibein).

In the case of the weak-field limit in (2+1)-dimensional empty space-time with a small positive cosmological constant, a non-linear Ricci curvature tensor (15) is reduced to a linearized Ricci curvature tensor (16). This small constant curvature accommodates our model in the limit of the infinite radius where the space-time is isotropic. What we mean by a linearized Ricci curvature tensor is, in terms of the spin connection, the Ricci curvature tensor is linear. We see

that a linearized Ricci curvature tensor in a gauge theory (19) is equivalent to a linearized curvature tensor in gravity theory (16).

The main difference between a non-Abelian and an Abelian gravity (a gauge theory) is that the curvature term, $\varepsilon_{bc}^a \omega_v^b \omega_\rho^c$, in gravity (15) or a gauge theory (18) no longer exists in a linearized curvature in gravity (16) or a gauge theory (19). In the case of the weak-field limit, the multiplication between the weak fields gives a very small result that we can assume to be ignored. It means no interaction exists between the spin connections in an Abelian gravity or an Abelian gauge theory. An Abelian Chern-Simons action (20) is a linear equation for the spin connection.

The dreibein formalism of general relativity makes general relativity similar to a gauge theory. For this reason, we need to reformulate the gauge potential related to the gauge (vector) fields, i.e. in terms of the dreibein and the spin connection, as written in eq. (34). Analogous to the vector potential (24), the gauge potential could be written using the Clebsch variables (35). The gauge potential is not a total derivative, otherwise, it would be a pure gauge [24]. A pure gauge in this context means the field configuration does not produce any observable curvature or field strength. Since the gauge potential is not a total derivative, it is not a pure gauge and represents a physical, non-trivial field configuration.

Analogous to the gauge potential, we assume that the gauge fields could be written using the Clebsch variables (37), (38). So, the relation between the gauge potential and the gauge fields could be written using the Clebsch variables (39). We could interpret the first term on the right-hand side (39), $f_e \partial_\mu q_e^a P_a$, as the rate of translation, f_e being an amplitude (scaling) factor that scales this translation rate. The second term on the right-hand side (39), $f_\omega \partial_\mu q_\omega^a$, shows the rate of rotation, f_ω being a scaling factor that scales this rotational rate.

Expressing the gauge potential and the gauge fields in terms of the Clebsch variables simplifies the formulation. The Clebsch variables, by showing explicitly the amplitude function and the phase, enable the separation of the underlying physical dynamics (the amplitude function, the phase) and certain properties of the gauge potential and the gauge fields, such as topological structures. Separating the gauge potential and the gauge fields into their amplitude function and phase makes the topological features (related to non-zero vorticity) inherent in the gauge potential and the gauge fields more apparent.

The problems in the higher dimension can often be more complex than those in the lower dimension. By mapping onto the lower dimensional space, such as in the non-trivial Hopf maps, the problem becomes simpler without losing the information about the non-trivial topological properties of space. If we relate the nontrivial Hopf maps to physics, we could interpret the Hopf maps to represent the properties of a set of curvature components consisting of complex scalar potentials. In the infinite radius, the value of the complex scalar potentials is weak. The complex scalar potentials have isotropic (well-defined) properties in the infinite radius.

We show that a set of curvature components satisfies the non-trivial Hopf maps (26). We assume that the time-independent problems of a set of curvature components, such as the electromagnetic knot, could be solved by interpreting some of the quantities that appear in Hopf's theories as Cauchy's initial time values.

There exists (one) dimensional reduction in the nontrivial Hopf maps. Physically, we could relate this dimensional reduction to the isotropic (well-defined) property of the complex scalar

potentials, the gauge potential, and the gauge fields. The isotropic (well-defined) property of the complex scalar potentials could be interpreted as an empty (a vacuum) space-time where spacetime is homogeneous (isotropic). A space-time without a source but with a small positive cosmological constant can be considered an empty space-time with a constant curvature (de Sitter space-time).

The non-zero constant curvature resulting from a small positive cosmological constant (40) is reflected in the non-commutativity between ∂_ν and ∂_ρ . This non-zero curvature is linked to the non-trivial (which can not be smoothly or continuously deformed into trivial configurations, such as a point) topological configurations of the gauge fields. In particular, the non-zero vorticity term $(\partial_\nu \partial_\rho - \partial_\rho \partial_\nu)q_\omega^a$, can contribute to a topological invariant, such as the winding number (an integer number). These non-trivial configurations are supporting evidence for the existence of the weak gravitational knot. The weak gravitational knot is related to the presence of the local vortex in space-time. The gravitation field could be imagined as a line (a field line) [32]. The winding number counts how often this field line winds around. The winding number is related to the field configuration's energy.

Theoretically, the empirical or the observational evidence to support the existence of the weak gravitational knot in (2+1)-dimensional empty space-time is guaranteed by the formal equivalence between the weak gravitational knot and the electromagnetic knot formulations for which the electromagnetic knot solutions had been known to exist [1, 11].

Experimentally, we could observe the existence of the weak gravitational knot by observing the gravitational wave (the ripples of space-time) as it passes through space-time influenced by the weak gravitational knot. The presence of topological structures, such as the weak gravitational knot, might influence the propagation of these ripples, detectable through their specific polarization modes. The weak gravitational knot could change the properties of the gravitational waves. These changes appear as additional or modified polarization modes (beyond the standard + and \times) in the detected gravitational waves.

So far, we are concerned with the weak gravitational knot in (2+1)-dimensional empty space-time with a small positive cosmological constant. This work could be extended to the case of the weak gravitational knot in (2+1)-dimensional empty space-time with a small negative cosmological constant (anti-de Sitter space-time).

The topological property of the Newtonian knot in (2+1)-dimensional empty space-time with a small positive cosmological constant related to the weak gravitational field and a very slow motion compared to the velocity of light is discussed separately [33].

Acknowledgment

We thank Caesnan Marendra Grahan Leditto, Richard Tao Roni Hutagalung, Idham Syah Alam, AI (Chat GPT) for fruitful discussions. Also, we would like to thank Reviewers for reviewing this article. MH thanks to beloved Juwita Armilia and Aliya Syauqina Hadi for much love. Al Fatihah for his Ibunda and Ayahanda. May Allah bless them with the highest level of heaven. This research is supported entirely by self-funding.

References

- [1] Antonio F Ranada, "Topological electromagnetism", *J. Phys. A: Math. Gen.* 25 (1992) 1621-1641.

- [2] Chen Ning Yang, "Topology and Gauge Theory in Physics", *International Journal of Modern Physics A*, Vol. 27, No. 30 (2012) 1230035.
- [3] Y. M. Cho, "Gauge theory, gravitation, and symmetry", *Physical Review D*, Volume 14, Number 12, 15 December 1976. Y. M. Cho, "Einstein Lagrangian as the translational Yang-Mills Lagrangian", *Physical Review D*, Volume 14, Number 10, 15 November 1976.
- [4] Edward Witten, "2+1 Dimensional Gravity as an Exactly Soluble System", *Nuclear Physics B* 311 (1988) 46-78. 5
- [5] Steven Carlip, "Quantum Gravity in 2+1 Dimensions", *Cambridge University Press*, 2003.
- [6] Bastian Wemmenhove, "Quantisation of 2+1 dimensional Gravity as a Chern-Simons theory", *Thesis, Instituut voor Theoretische Fysica*, Amsterdam, 2002.
- [7] Wouter Merbis, "Chern-Simons-like Theories of Gravity", *Ph.D. Thesis, University of Groningen*, 2014.
- [8] Roman Jackiw, "Diverse Topics in Theoretical and Mathematical Physics", *World Scientific*, 1995.
- [9] Roman Jackiw, "Lower Dimensional Gravity", *Nuclear Physics B* 252 (1985) 343-356.
- [10] Jorge Zanelli, "Chern-Simons Gravity: From 2+1 to 2n+1 Dimensions", *Brazilian Journal of Physics*, Vol. 30, No.2, June 2000.
- [11] A. V. Crisan, C. R. L. Godinho, I. V. Vancea, "Gravitoelectromagnetic knot fields", *arXiv:2103.00217v1 [gr-qc]* 27 Feb 2021
- [12] Y. M. Cho, Seung Hun Oh, Pengming Zhang, "Knots in Physics", *International Journal of Modern Physics A*, Vol. 33, No. 07, 1830006 (2018).
- [13] Y. M. Cho, Franklin H. Cho and J.H. Yoon, "Vacuum decomposition of Einstein's theory and knot topology of vacuum space-time", *Class. Quantum Grav.* 30 (2013) 055003 (17pp).
- [14] Michael Atiyah, "The Geometry and Physics of Knots", *Cambridge University Press*, 1990.
- [15] Ji-rong Ren, Ran Li, Yi-shi Duan, "Inner topological structure of Hopf invariant", <https://arxiv.org/abs/0705.4337v1>, 2007.
- [16] Yi-shi Duan, Xin Liu, Li-bin Fu, "Many knots in Chern-Simons field theory", *Physical Review D* 67, 085022 (2003).
- [17] Antonio F. Ranada, "A Topological Theory of the Electromagnetic Field", *Letters in Mathematical Physics* 18: 97-106, 1989.
- [18] P. A. M. Dirac, "General Theory of Relativity", *John Wiley & Sons*, 1975.
- [19] K. Surya Kiran, Chethan Krishnan, Avinash Raju, "3D Gravity, Chern-Simons and Higher Spins: A Mini Introduction", *arXiv:1412.5053v3 [hep-th]* 15 Sep 2015.
- [20] Manfredo P. do Carmo, "Differential Geometry of Curves and Surfaces", *Prentice Hall Inc.*, 1976.
- [21] Mark Srednicki, "Quantum Field Theory", *Cambridge University Press*, 2007.
- [22] James B. Hartle, "Gravity: An Introduction to Einstein's General Relativity", *Pearson*, 2014.

- [23] Miftachul Hadi, "Knot in weak-field geometrical optics", *OSF*, <https://osf.io/e7aff/>, 2023, and all references therein.
- [24] A. F. Ranada, A. Tiemblo, "A Topological Structure in the Set of Classical Free Radiation Electromagnetic Fields", *arXiv:1407.8145v1 [physics.class-ph]* 29 Jul 2014.
- [25] Roman Jackiw, "Lectures on Fluid Dynamics", *Springer*, 2002.
- [26] Miftachul Hadi, Hans Jacobus Wospakrik, "SU(2) Skyrme Model for Hadron", <https://arxiv.org/abs/1007.0888>, 2010.
- [27] Miftachul Hadi, Irwandi Nurdin, Denny Hermawanto, "Analytical Analysis and Numerical Solution of Two Flavours Skyrmeion", <https://arxiv.org/abs/1006.5601>, 2010.
- [28] J. H. C. Whitehead, "An Expression of Hopf's Invariant as an Integral", *Proceedings of the National Academy of Sciences*, Vol. 33, No. 5, 117-123, 1947.
- [29] Raoul Bott, Loring W. Tu, "Differential Forms in Algebraic Topology", *Springer*, 1982.
- [30] John Baez, Javier P. Muniain, "Gauge Fields, Knots and Gravity", *World Scientific*, 1994.
- [31] M.P. Hobson, G.P. Efstathiou, A.N. Lasenby, "General Relativity: An Introduction for Physicists", *Cambridge University Press*, 2006.
- [32] Charles W. Misner, Kip S. Thorne, John Archibald Wheeler, "Gravitation", *W. H. Freeman and Company*, 1973.
- [33] Amy Thompson, Alexander Wickes, Joe Swearngin, Dirk Bouwmeester, "Classification of Electromagnetic and Gravitational Hopfions by Algebraic Type", *arXiv:1411.2073v2 [gr-qc]* 2 May 2015.
- [34] Miftachul Hadi, "On Newtonian knot in (2+1)-dimensional empty space-time", *OSF*, <https://osf.io/preprints/osf/su3dp>, 2024, and all references therein