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DIFFERENT APPROACHES TO THE EINSTEIN ENERGY ASSOCIATED WITH THE de SITTER C-SPACE-TIME

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The paper is purposed to elaborate the problem of gravitational energy localization in de Sitter(dS) C-space-time (the C space-time in a background with a cosmological constant Λ). In this connection, using the energy-momentum definition of Einstein, we find the same energy in both general relativity and tele-parallel gravity.

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1 Introduction

The problem of energy-momentum localization has been one of the most interesting and thorny problems which remains unsolved since the advent of general relativity. Misner, Thorne and Wheeler [1] showed that the energy is localizable only for spherical systems. Later, Cooperstock and Sarracino [2] contradicted their viewpoint and showed that if the energy is localizable in spherical systems then it is also localizable for all systems and Bondi [3] expressed that a non-localizable form of energy is inadmissible in relativity. Cooperstock [4] hypothesized that in a curved space-time energy and momentum are confined to the region of non-vanishing energy-momentum tensor $T_{\mu\nu}$ and consequently the gravitational waves are not carriers of energy-momentum in vacuum space-times. This hypothesis has neither been proved nor disproved. There are many results which support this hypothesis [5]. It would be interesting to investigate the cylindrical gravitational waves in vacuum space-times.

Ever since the Einstein energy-momentum complex [6] has been used for calculating the energy-momentum distribution in a general relativistic system, many attempts have been made to evaluate the energy distribution for a given space-time [7–13]. Except the one which was defined by Møller, these definitions give meaningful results if the calculations are performed in "Cartesian" coordinates. Møller constructed an expression which enables one to evaluate energy and momentum in any coordinate system.

Several examples of particular space-times have been investigated and different energy-momentum pseudo-tensors are known to give the same energy distribution for a given space-time [14–21]. Virbhadra [15], using the energy and momentum complexes of Einstein, Landau-Lifshitz, Papapetrou and Weinberg for a general non-static spherically symmetric space-time of

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the Kerr-Schild class metric, showed that all of these energy-momentum formulations give the same energy distribution as in the Penrose energy-momentum formulation.

Recently, the problem of the energy-momentum localization has also been considered in tele-parallel gravity [22–24]. The authors found that energy-momentum also localize in this alternative theory, and their results agree with some of the previous papers which were studied in the general theory of relativity. Vargas [24], using the definitions of Einstein and Landau-Lifshitz in tele-parallel gravity, found that the total energy is zero in Friedmann-Robertson-Walker space-time. Later, with my collaborators, in both general relativity and tele-parallel gravity, I obtained the results which agree with each other and the previous ones [20, 21, 25–28].

So, in this paper, we evaluate the energy of de Sitter C (dS-C) space-time by using the Einstein energy-momentum complex and its tele-parallel gravity analog[2].

2 The dS C-metric

The massive charged dS C-metric has been found by Plebanski and Demianski [29], and its gravitational field can be written as (see e.g. [30])

$$ds^2 = -\Omega^2 \mathrm{d}t^2 + \Delta^2 \mathrm{d}x^2 + \Sigma^2 \mathrm{d}y^2 + \Pi^2 \mathrm{d}z^2, \tag{1}$$

where

$$\Omega(x,y) = \frac{\sqrt{\Upsilon}}{A(x+y)}, \qquad \Delta(x,y) = \frac{1}{A(x+y)\sqrt{G}}, \tag{2}$$

$$\Sigma(x,y) = \frac{1}{A(x+y)\sqrt{\Upsilon}}, \qquad \Pi(x,y) = \frac{\sqrt{G}}{A(x+y)} \tag{3}$$

with

$$\Upsilon(y) = -\frac{\Lambda + 3A^2}{3A^2} + y^2 - 2mAy^3 + q^2A^2y^4, \tag{4}$$

$$G(x) = 1 - x^2 - 2mAx^3 - q^2A^2x^4. \tag{5}$$

This solution depends on four parameters namely, the cosmological constant Λ, $A > 0$ which is the acceleration of the black holes, and m and q which are the interpreted as electro magnetic charge of the non-accelerated black hole. The physical properties and interpretation of this solution have been analyzed by Dias and Lemos [30], and by Podolsky and Griffiths [31].

The matrices of the $g_{\mu\nu}$ and $g^{\mu\nu}$ are defined respectively by

$$\begin{pmatrix} -\Omega^2 & 0 & 0 & 0 \\ 0 & \Delta^2 & 0 & 0 \\ 0 & 0 & \Sigma^2 & 0 \\ 0 & 0 & 0 & \Pi^2 \end{pmatrix}, \qquad \begin{pmatrix} -\Omega^{-2} & 0 & 0 & 0 \\ 0 & \Delta^{-2} & 0 & 0 \\ 0 & 0 & \Sigma^{-2} & 0 \\ 0 & 0 & 0 & \Pi^{-2} \end{pmatrix} \tag{6}$$

[2] *Notations and conventions*: we use convention that $c = h = 1$, and metric signature $(-, +, +, +)$. In this paper, Greek and Latin indices run from 0 to 3 otherwise stated.

and $g = \det(g_{\mu\nu}) = -\Omega^2\Delta^2\Sigma^2\Pi^2$. The non-trivial tetrad field induces a tele-parallel structure on space-time which is directly related to the presence of the gravitational field, and the Riemannian metric arises as

$$g_{\mu\nu} = \eta_{ab} h^a{}_\mu h^b{}_\nu, \qquad \eta_{ab} = \mathrm{diag}(-1, 1, 1, 1). \tag{7}$$

Using this relation, we obtain the tetrad components $h^a{}_\mu$ as follow:

$$h^a{}_\mu = \begin{pmatrix} -\Omega & 0 & 0 & 0 \\ 0 & \Delta & 0 & 0 \\ 0 & 0 & \Sigma & 0 \\ 0 & 0 & 0 & \Pi \end{pmatrix} \tag{8}$$

and its inverse

$$h_a{}^\mu = \begin{pmatrix} -\Omega^{-1} & 0 & 0 & 0 \\ 0 & \Delta^{-1} & 0 & 0 \\ 0 & 0 & \Sigma^{-1} & 0 \\ 0 & 0 & 0 & \Pi^{-1} \end{pmatrix}, \tag{9}$$

where $h = \det(h^a{}_\mu) = \Omega\Delta\Sigma\Pi$.

3 Energy in General Relativity

The energy-momentum prescription of Einstein [6] is given by

$$\Theta^\nu_\mu = \frac{1}{16\pi} H^{\nu\alpha}_{\mu,\alpha}, \tag{10}$$

where

$$H^{\nu\alpha}_\mu = \frac{g_{\mu\beta}}{\sqrt{-g}} \left[-g(g^{\nu\beta} g^{\alpha\xi} - g^{\alpha\beta} g^{\nu\xi})\right]_{,\xi}. \tag{11}$$

The Θ^0_0 is the energy density, Θ^0_α are the momentum density components, and Θ^α_0 are the components of energy current density. The Einstein energy and momentum density satisfies the local conservation laws

$$\frac{\partial \Theta^\nu_\mu}{\partial x^\nu} = 0. \tag{12}$$

and energy and momentum components are given by

$$P_\mu = \int\int\int \Theta^0_\mu \mathrm{d}x \mathrm{d}y \mathrm{d}z. \tag{13}$$

Further Gauss's theorem furnishes

$$P_\mu = \frac{1}{16\pi} \int\int H^{0\lambda}_\mu \eta_\lambda \mathrm{d}S, \tag{14}$$

where η_λ ($\lambda = 1, 2, 3$) stands for the 3-components of unit vector over an infinitesimal surface element $dS = r^2 \sin\theta \mathrm{d}\theta \mathrm{d}\phi$. The P_i give momentum(energy current) components P_1, P_2, P_3 and P_0 gives the energy.

Considering the line-element (1), then the required non-vanishing components of $H_\mu^{\nu\alpha}$ are found as:

$$H_0^{01} = \frac{2\Omega}{\Delta}(\Sigma\Pi)_x, \qquad H_0^{02} = \frac{2\Omega}{\Sigma}(\Delta\Pi)_y, \tag{15}$$

where x and y indices describe the derivative with respect to x and y. Next, using equation (10) we obtain the following energy

$$\begin{aligned} \Theta_0^0 &= \frac{1}{16\pi}\left(\frac{\partial}{\partial x}H_0^{01} + \frac{\partial}{\partial y}H_0^{02}\right) \\ &= \frac{1}{8\pi}\left[(\frac{\Omega}{\Delta})_x(\Sigma\Pi)_x + \frac{\Omega}{\Delta}(\Sigma\Pi)_{xx} + (\frac{\Omega}{\Sigma})_y(\Delta\Pi)_y + \frac{\Omega}{\Sigma}(\Delta\Pi)_{yy}\right]. \end{aligned} \tag{16}$$

In the special case, the energy density associated with the dS-C metric is given below.

$$\Theta_0^0 = hE^0{}_0 = \frac{(x+y)^{-2}}{16\pi A^2}\left[\frac{G_{xx}}{2} + \frac{(x+y-2)\Upsilon_y - 3G}{x+y} + \frac{6G - 2\Upsilon(x+y-3)}{(x+y)^2}\right], \tag{17}$$

where

$$\Upsilon(y) = -\frac{\Lambda + 3A^2}{3A^2} + y^2 - 2mAy^3 + q^2A^2y^4, \tag{18}$$

$$G(x) = 1 - x^2 - 2mAx^3 - q^2A^2x^4. \tag{19}$$

Using exact form of the functions $G(x)$ and $\Upsilon(y)$ given above, the energy density with cosmological constant is found exactly as [32, 33]:

$$\begin{aligned} \Theta_0^0 = hE^0{}_0 \;=\; & \frac{(x+y)^{-4}}{48\pi\, A^4}[3y^2A^2 - 6\Lambda^2 - 6q^2A^4y^4 - 45mA^3x^3 - 36q^2A^4x^4 - 6mA^3y^4 \\ & +6q^2A^4y^5 + 6xy^2 - 18A^2xy + 12A^3mx^4 + 6A^4q^2x^5 - 21x^2A^2 \\ & +2(x+y)\Lambda^2 + 6A^2x^3 - 24mxA^3y^3 + 18xq^2A^4y^4 - 18myx^2A^3 \\ & +27mxy^2A^3 - 36q^2A^4x^3y - 18q^2A^4x^2y^2 - 24A^4xy^3q^2 + 12A^2yx^2 \\ & -18A^3x^2my^2 + 12A^4x^2q^2y^3 + 12A^3mx^3y + 6A^4q^2x^4y] \end{aligned} \tag{20}$$

and the energy density without cosmological constant is

$$\begin{aligned} \Theta_0^0 = hE^0{}_0 \;=\; & \frac{(x+y)^{-4}}{48\pi A^4}[3y^2A^2 - 6q^2A^4y^4 - 45mA^3x^3 - 36q^2A^4x^4 - 6mA^3y^4 \\ & +6q^2A^4y^5 + 6xy^2 - 18A^2xy + 12A^3mx^4 + 6A^4q^2x^5 - 21x^2A^2 \\ & +6A^2x^3 - 24mxA^3y^3 + 18xq^2A^4y^4 - 18myx^2A^3 \\ & +27mxy^2A^3 - 36q^2A^4x^3y - 18q^2A^4x^2y^2 - 24A^4xy^3q^2 + 12A^2yx^2 \\ & -18A^3x^2my^2 + 12A^4x^2q^2y^3 + 12A^3mx^3y + 6A^4q^2x^4y]. \end{aligned} \tag{21}$$

4 Energy in Tele-parallel gravity

Tele-parallel gravity is an alternative approach to gravitation [34, 35] which corresponds to a gauge theory for the translation group based on the Weitzenböck geometry [36]. In this theory, gravitation is attributed to torsion [37], which plays the role of a force [38], whereas the curvature tensor vanishes identically. The fundamental field is represented by a nontrivial tetrad field, which gives rise to the metric as a by-product. The last translational gauge potentials appear as the nontrivial part of the tetrad field, thus induces on space-time a tele-parallel structure which is directly related to the presence of the gravitational field. The interesting point of tele-parallel gravity is that, due to gauge structure, it can reveal a more appropriate approach to consider same specific problem. This is the case, for example, of the energy-momentum problem, which becomes more transparent when considered from the tele-parallel point of view.

The tele-parallel gravity analog of Einstein energy-momentum complex [24] is given by:

$$hE^{\mu}{}_{\nu} = \frac{1}{4\pi}\partial_{\lambda}(U_{\nu}{}^{\mu\lambda}), \tag{22}$$

where $h = \det(h^{a}{}_{\mu})$ and $U_{\beta}{}^{\nu\lambda}$ is the Freud's super-potential, which is given by:

$$U_{\beta}{}^{\nu\lambda} = hS_{\beta}{}^{\nu\lambda}. \tag{23}$$

Here $S^{\mu\nu\lambda}$ is the tensor

$$S^{\mu\nu\lambda} = k_1 T^{\mu\nu\lambda} + \frac{k_2}{2}(T^{\nu\mu\lambda} - T^{\lambda\mu\nu}) + \frac{k_3}{2}(g^{\mu\lambda}T^{\beta\nu}{}_{\beta} - g^{\nu\mu}T^{\beta\lambda}{}_{\beta}) \tag{24}$$

with k_1, k_2 and k_3 the three dimensionless coupling constants of tele-parallel gravity [37]. For the tele-parallel equivalent of general relativity the specific choice of these three constants are:

$$k_1 = \frac{1}{4}, \qquad k_2 = \frac{1}{2}, \qquad k_3 = -1. \tag{25}$$

To calculate this tensor firstly we must calculate Weitzenböck connection:

$$\Gamma^{\alpha}{}_{\mu\nu} = h_{a}{}^{\alpha}\partial_{\nu}h^{a}{}_{\mu} \tag{26}$$

and after this calculation we get torsion of the Weitzenböck connection:

$$T^{\mu}{}_{\nu\lambda} = \Gamma^{\mu}{}_{\lambda\nu} - \Gamma^{\mu}{}_{\nu\lambda}. \tag{27}$$

For the Einstein complex, we have the relation,

$$P_{\mu} = \int_{\Sigma} hE^{0}{}_{\mu}\mathrm{d}x\mathrm{d}y\mathrm{d}z, \tag{28}$$

where P_i give momentum components P_1, P_2, P_3 while P_0 gives the energy and the integration hyper-surface Σ is described by $x^0 = t =$constant.

For the dS-C space-time, the non-vanishing components of the Weitzenböck connection are obtained as:

$$\Gamma^{0}{}_{01} = \frac{\Omega_x}{\Omega}, \qquad \Gamma^{0}{}_{02} = \frac{\Omega_y}{\Omega}, \tag{29}$$

$$\Gamma^1{}_{11} = \frac{\Delta_x}{\Delta}, \qquad \Gamma^1{}_{12} = \frac{\Delta_y}{\Delta}, \tag{30}$$

$$\Gamma^2{}_{21} = \frac{\Sigma_x}{\Sigma}, \qquad \Gamma^2{}_{22} = \frac{\Sigma_y}{\Sigma}, \tag{31}$$

$$\Gamma^3{}_{31} = \frac{\Pi_x}{\Pi}, \qquad \Gamma^3{}_{32} = \frac{\Pi_y}{\Pi}. \tag{32}$$

The corresponding non-vanishing torsion components are found:

$$T^0{}_{10} = -T^0{}_{01} = \frac{\Omega_x}{\Omega}, \qquad T^0{}_{20} = -T^0{}_{02} = \frac{\Omega_y}{\Omega}, \tag{33}$$

$$T^1{}_{21} = -T^1{}_{12} = \frac{\Delta_y}{\Delta}, \tag{34}$$

$$T^2{}_{12} = -T^2{}_{21} = \frac{\Sigma_x}{\Sigma}, \tag{35}$$

$$T^3{}_{13} = -T^3{}_{31} = \frac{\Pi_x}{\Pi}, \qquad T^3{}_{23} = -T^3{}_{32} = \frac{\Pi_y}{\Pi}. \tag{36}$$

Taking these results into equation (24), the required non-vanishing components of the tensor $S_\mu{}^{\nu\lambda}$ are calculated as:

$$S^{001} = \frac{1}{2(\Omega\Delta)^2}\frac{(\Sigma\Pi)_x}{\Sigma\Pi}, \tag{37}$$

$$S^{002} = \frac{1}{2(\Omega\Sigma)^2}\frac{(\Delta\Pi)_y}{\Delta\Pi}. \tag{38}$$

Now, using equation (23) the non-vanishing components of Freud's super-potential are:

$$U_0^{01} = \frac{\Omega}{2\Delta}(\Sigma\Pi)_x, \qquad U_0^{02} = \frac{\Omega}{2\Sigma}(\Delta\Pi)_y. \tag{39}$$

Using equation (22) with these results, Einstein's energy density is found as:

$$\begin{aligned} hE^0{}_0 &= \frac{1}{4\pi}\left(\frac{\partial}{\partial x}U_0^{01} + \frac{\partial}{\partial y}U_0^{02}\right) \\ &= \frac{1}{8\pi}\left[(\frac{\Omega}{\Delta})_x(\Sigma\Pi)_x + \frac{\Omega}{\Delta}(\Sigma\Pi)_{xx} + (\frac{\Omega}{\Sigma})_y(\Delta\Pi)_y + \frac{\Omega}{\Sigma}(\Delta\Pi)_{yy}\right]. \end{aligned} \tag{40}$$

This is the same energy as obtained in general relativity.

5 Discussion

The main object of the presented paper is to show that it is possible to evaluate the energy distribution by using the energy-momentum formulations in not only general relativity but also teleparallel gravity. To compute the energy density(due to matter and fields including gravitation), we considered two different approaches of the Einstein energy-momentum definition. We found that the energy distribution associated with the dS-C space-time is the same in both general relativity and tele-parallel gravity. Next, our results advocate the importance of energy-momentum complexes(opposes the against that different complexes could give different meaningless results for a given metric). The energy distribution is also dependent of the tele-parallel dimensionless coupling constants, which means that it is valid only in the tele-parallel equivalent of general relativity, it is not valid any tele-parallel model.

Appendix: Kinematical Quantities

After the pioneering works of Gamow [39] and Gödel [40], the idea of global rotation of the universe has became considerably important physical aspect in the calculations of general relativity. Now, we introduce a tetrad basis by

$$\theta^0 = \Omega \mathrm{d}t, \qquad \theta^1 = \Delta \mathrm{d}x, \qquad \theta^2 = \Sigma \mathrm{d}y, \qquad \theta^3 = \Pi \mathrm{d}z. \tag{41}$$

By use of the co-moving tetrad formalism, the kinematics of this model can be expressed solely in terms of the structure coefficients of the tetrad basis. We define the structure coefficients by

$$d\theta^\alpha = \frac{1}{2} C^\alpha_{\beta\gamma} \theta^\beta \wedge \theta^\gamma. \tag{42}$$

By taking the exterior derivatives of the tetrad basis given above and using the kinematics formulas [41, 42];

Kinematical Quantity	Definition
Four-acceleration vector:	$a_\mu = C^0_{\mu 0}$
vorticity tensor:	$\omega_{\mu\nu} = \frac{1}{2} C^0_{\mu\nu}$
expansion(deformation) tensor:	$\xi_{\mu\nu} = \frac{1}{2}(C_{\mu 0 \nu} + C_{\nu 0 \mu})$
expansion scalar:	$\xi = C^1_{01} + C^2_{02} + c^3_{03}$
vorticity vector:	$\omega^1 = \frac{1}{2} C^0_{23}, \qquad \omega^2 = \frac{1}{2} C^0_{31}, \qquad \omega^3 = \frac{1}{2} C^0_{12}$
vorticity scalar:	$\omega = \frac{1}{4}\sqrt{(C^0_{23})^2 + (C^0_{31})^2 + (C^0_{12})^2}$
shear tensor:	$\sigma_{\mu\nu} = \xi_{\mu\nu} - \frac{1}{3}\xi \delta_{\mu\nu}$

Tab. 1. List of kinematical quantities and their formulas.

We find the following quantities for the line element given by equation (1):

$$\xi_{\mu\nu} = \xi = \sigma_{\mu\nu} = w = w^i = 0, \qquad (i = 1, 2, 3) \tag{43}$$

$$a_1 = \frac{2\Omega_x}{\Omega \Delta}, \qquad a_2 = \frac{2\Omega_y}{\Omega \Sigma}. \tag{44}$$

From these results we see that the model given in (1) has no-expansion and the metric is shear-free. We also note that this model has non-vanishing two components of the four-acceleration vector and vanishing vorticity vector.

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