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Gravity and Information II

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Abstract: In a recent paper, we have shown how gravity and information can be related. The relation is based on the thermodynamic extension of the gravitational system under consideration using the holographic principle. Using this idea, we were able to derive the Gullstrand-Painlevé (GP) metric. In this short paper, we re-derive the GP metric using information. However, we now extend the spacetime to 5D with the fifth dimension being time, that is, the (3+1)D spacetime is now promoted to (3+1+1)D spacetime. We also comment on the possible Braneworld interpretation of this model.

Keywords: extra time dimension; holographic principle; thermodynamics and gravity

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1. Introduction

In a recent paper [1], we have described how gravity and information can be related. This relation is used to obtain the Gullstrand-Painlevé (GP) metric in a very non-trivial way. The GP metric and the familiar Schwarzschild metric are related to each other merely by a coordinate transformation. Thus, the information approach explains (hopefully atleast!) all four classical tests of gravity in a novel way. The main idea was to connect thermodynamics and gravity. The idea dates back to the seminal works of Hawking and Bekenstein [2–5] in which they showed that area and entropy are related resulting in the famous Bekenstein-Hawking entropy equation. In a seminal paper published in 1995, Jacobson [6] derived the classical Einstein's equation using local thermodynamic equilibrium conditions using the relation $\delta Q = T\delta S$. The connection between gravity and thermodynamics was further explored by Padmanabhan (see [7] for a review). Quite recently, Verlinde [8] used the holographic principle to obtain Newton's law from an entropic force perspective. All these strongly suggest that there must be a deep connection between gravity and thermodynamics. In this short paper, we re-derive the GP metric using information. But now we consider the 5D spacetime with the fifth dimension being "time", that is, the (3+1)D spacetime is promoted to (3+1+1)D spacetime. In the next section, we first revisit the connection between gravity and thermodynamics (this section follows from [1]).

2. Gravity and Information Relation: Revisited

Let us first define some quantities relevant to our discussion and approach. Consider the system consisting of a source mass M and a boundary. The "boundary" here is a data-storing surface such as a holographic screen (see Figure 1). Motivated by the Bekenstein bound [9], let us define a quantity C_D as the maximum degrees of freedom associated with the mass M at a distance R from the boundary as[1]

$$C_D = \frac{2\pi RM}{\hbar} \tag{1}$$

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[1] We set $k_B = c = 1$

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Another quantity C_I is defined as the maximum degrees of freedom available. This is assumed to follow the holographic principle [10,11] which has strong pieces of evidence from the AdS/CFT correspondence [12] and black hole physics [4,5], such that the information about the volume of space is stored on the boundary. Thus we assume that the total degrees of freedom is given by

$$N = \frac{A}{l_p^2} \tag{2}$$

where A is the surface area of the boundary and l_p is the Planck length. Therefore

$$C_I = N = \frac{A}{l_p^2} \tag{3}$$

The "disorder" D in the system which gives the ratio of the maximum degrees of freedom of the mass M to the maximum available degrees of freedom is therefore given by[2]

$$D = \frac{C_D}{C_I} \tag{4}$$

Now that we have defined some important quantities needed to present our approach, we turn toward a specific and important property of the boundary which is the temperature T. This can be found by invoking the use of the boundary as a holographic screen that can store data, thus as an object comes near this holographic screen, its total energy (per unit mass) given b $p_0 u^0$ is stored on the boundary as evenly bits of information N. Since the distribution is even, we can use our good old equipartition rule of thermodynamics to find the temperature of the boundary as

$$p_0 u^0 = \frac{1}{2} N T \tag{5}$$

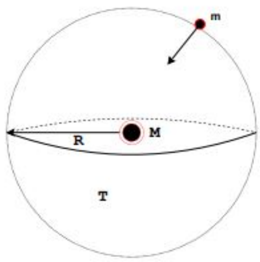

Figure 1. Our system consists of a source mass M and a "boundary" which is a data-storing surface such as a holographic screen. T is the temperature of the bounding surface arising from the even distribution of the total energy E of the mass m as N bits of information as it approaches the holographic boundary.

[2] see [13]

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3. Thermodynamic Energy and Static and Spherically symmetric solution

The internal energy of the system due to its thermodynamic nature is defined by [1]

$$U = TS \tag{6}$$

where T is the temperature of the boundary and S is given by C_D. The total degrees of freedom on the boundary is

$$N = \frac{A}{l_p^2} = \frac{4\pi r^2}{l_p^2} \tag{7}$$

Thus the total energy of the thermodynamic system is

$$U = TS = \frac{M}{r}\left(\frac{dt}{d\tau}\right)^2 \tag{8}$$

We extend the spacetime to 5D (3+1+1) with μ varying from -1 to 3, such that the fifth dimension is time with metric component -1. And the total energy in the (3+1+1) spacetime is given by

$$E = p_{-1}u^{-1} = \left(\frac{dT}{d\tau}\right)^2 \tag{9}$$

Using Smarr's formula, we have the relation $E = 2TS = 2U$, this gives

$$dT^2 = \frac{2M}{r}dt^2 \tag{10}$$

The spacetime interval is given as

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu \tag{11}$$

where $g_{\mu\nu}$ is the fixed $5D$ background spacetime. Hence in the spherical coordinates, we get the most general static (in observable or "physical time" t) and spherically symmetric metric as

$$ds^2 = dt^2 - dr^2 - r^2(d\theta^2 + sin^2\theta d\phi^2) - dT^2 - 2dTdr \tag{12}$$

Note that the cross term $dtdT$ is not present since this term is not invariant under (physical time transformation) $dt \to -dt$. Thus, (12) becomes (using 10)

$$ds^2 = dt^2 - dr^2 - r^2(d\theta^2 + sin^2\theta d\phi^2) - \frac{2M}{r}dt^2 - 2\sqrt{\frac{2M}{r}}dtdr \tag{13}$$

(13) is the Gullstrand-Painlevé metric and a coordinate transformation converts it to the well-known Schwarzschild metric given as

$$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \left(1 - \frac{2M}{r}\right)^{-1}dr^2 - r^2(d\theta^2 + sin^2\theta d\phi^2) \tag{14}$$

This model of extending the (3+1) dimensions to (3+1+1) can be a given a nice Braneworld interpretation. This model can be considered as (3+1)D brane in (3+1+1)D bulk. Matter and all the standard model particles and fields are localized on the brane while only gravity moves through bulk. Instead of saying that gravity (being a force mediated by particles) moves through the bulk, we can say that the extra time dimension through its presence in the spacetime interval affects the geodesics of particles on the brane. So, instead of interpreting that gravity has access to bulk (if gravity were force mediated by graviton that can propagate through bulk), we should interpret it as: The extra time dimension of the bulk creates the illusion of gravity on the brane in presence of matter field on the brane.

4. Conclusion and Future Work

In this short paper, we successfully re-derived the Gullstrand-Painlevé (GP) metric using information. The approach required the extension of (3+1)D spacetime to (3+1+1)D spacetime. We again reiterate that the way gravity affects time strongly suggests that gravity can not be a force in the usual sense. We did the thermodynamic extension of the gravitational system by using the holographic principle which says that the degrees of freedom scale as area rather than the volume of space. Finally, the GP metric can be converted to the Schwarzschild metric through a coordinate transformation and, therefore, all the four classical tests of gravity (which are based on this metric) hold in this formalism as well. We also gave an interesting Braneworld interpretation of this model and argued that gravity is not a force being mediated by particles that can access the bulk as is usually considered. Rather, the extra time dimension of the bulk through its presence in the spacetime interval creates the illusion of gravity. Our future work aims to describe gravitational waves using this approach which is not immediately clear to us. Moreover, whether this approach can be framed in an effective field theory..? If yes, how..? is an open and challenging question for us as of now.

Conflicts of Interest: The author declares no conflict of interest.

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